Novel Three-dimensional Hollow-core Waveguide Using High-contrast Sub-wavelength Grating

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Abstract: A novel hollow-core waveguide using high-contrast sub-wavelength grating (HCG) is experimentally demonstrated for the first time. The waveguide is formed by two HCG planar structures and shows both transverse and lateral light confinement.

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1. Introduction

Hollow-core waveguides (HWs) have a wide range of applications in gas sensing and gas-based nonlinear optics. With the elimination of core material, nonlinearity, dispersion effects and scattering losses in traditional SiO_2, Si or III-V waveguides can be drastically reduced. Chip-scale HWs would open up a new range of on-chip applications such as optical buffers, optical signal processors, and RF filtering. Optical beam in a hollow-core waveguide is guided by zig-zag reflections of highly reflective layers such as distributed Bragg reflectors [1] and antiresonant reflection layers [2]. However, it is challenging to achieve lateral confinement in those configurations. Recently, we proposed a novel HW using high contrast sub-wavelength grating (HCG) as reflectors [3]. In this paper, we experimentally demonstrate such waveguides with HCGs fabricated on silicon-on-insulator (SOI) wafers. Two parallel, planar wafers containing HCG layers are shown to confine light in both transverse and lateral directions. Furthermore, an entirely new waveguide geometry has emerged with grating running parallel to wave propagation.

2. HCG-HW design

HCG has been demonstrated as a high reflection mirror at normal incident angle for VCSELs [3]. Although we showed by simulation that high reflection can be obtained at small glancing angles for hollow-core waveguides [3], this work represents the first experimental demonstration. Figure 1 shows the schematics of HCG and HCG-HW. The HCG is fabricated on an SOI wafer with Si gratings on top of a SiO_2 layer. The direction of light propagation can be either perpendicular or parallel to the HCG bars depending on designs. The latter one is chosen in this work mainly because of larger fabrication tolerance. Lateral confinement is achieved by choosing different HCG period as well as air gap for the core and cladding region. These two HCG designs provide different reflection phases, and thus their effective indices (as a slab waveguide) are different. We design the HCG period (Λ) and air gap (a) to be 1190 nm and 450 nm for core region, and 1000 nm and 380 nm for the cladding region; HCG thickness (t_g) is 340 nm for both core and cladding. The oxide underneath is 2 µm thick. With a 5 µm waveguide height (D) and 1.55 µm light, the relative effective index difference between core and cladding is calculated to be ~0.25%, as confirmed by both rigorous coupled wave analysis (RCWA) and finite element method (FEM). Propagation loss of core and cladding (as a slab waveguide) is calculated to be 0.12 dB/m and 2.5 dB/m respectively in RCWA. We expect the total propagation loss of the 2D confined waveguide to be closer to the value for the core.

Figure 2(a) shows the guided mode profile simulated by FEM. A single optical mode is well-confined in the 13 µm (W_c) core region (Total waveguide width is 55 µm). Although the majority of the propagation medium is air, with only minor interaction between the light and Si HCG, a small parameter change of the HCG is able to generate enough reflection phase difference to confine the light laterally. To the best of our knowledge, this is the first experimental device showing lateral confinement in a planar hollow-core waveguide structure.

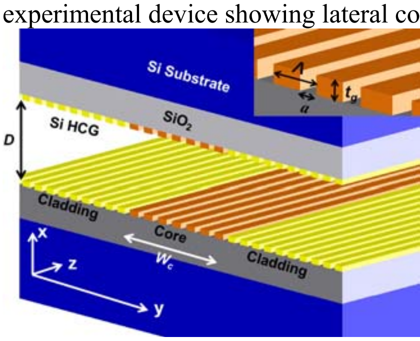

Fig. 1. Schematics of HCG-HW. Si HCG sits on top of a SiO_2 layer and Si substrate. Core and cladding

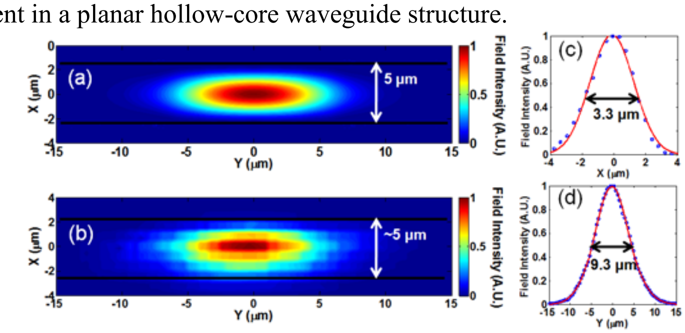

Fig. 2. Propagation mode profile of the designed HCG-HW simulated by FEM (a) and the fabricated device measured in experiment (b). (c) The measured transverse mode

have different HCG designs. *D*, waveguide height. W_c, core width. Indent, schematics of HCG. Λ: period; *a*: air gap; t_g: thickness.

profile (blue dots) is fitted with Gaussian function (red line). (d) The measured lateral mode profile (blue dots) is fitted with cosinoidal function in core region and Gaussian function in cladding region (red line).

3. HCG-HW fabrication and testing

The HCG-HW is fabricated using a 6’’ SOI wafer. The actual thickness of the Si layer on the SOI wafer is 10 nm thinner than the 340 nm designed value. This decreases the simulated reflectivity of HCG at 1.55 µm. This can be partially, though not fully, compensated by changing the launching wavelength to 1.48 µm, and reducing the air gap of both core and cladding HCG by 10 nm. The HCG is patterned with DUV lithography on the device layer, followed by a standard Si dry etching. Figure 3 shows the SEM image. Two pieces of patterned HCG chips are then mounted to two translation stages, and brought close to each other to form the waveguide. A 40X objective is used to launch the collimated laser beam into the waveguide, as well as for input facet imaging. A 50X objective is used to collect the light for loss measurement as well as for output facet imaging. With precise alignment of the two chips, an optical mode can be seen at the output facet (*D*~5 µm), shown in Fig. 2(b). The FWHMs are ~3.3 and ~9.3 µm in the transverse and lateral direction, respectively, [Fig. 2(c)(d)]. Excellent agreement is obtained with simulation, shown in Fig. 2(a).

The design differences of HCGs for core and cladding regions are really small, but its impact is great. In fact, both designs provide transverse guiding. However, they yield slightly different propagation constants for a given *D*, which thus provides the lateral guiding (by effective index analysis). As *D* increases, the effective index difference decreases, resulting in a weaker lateral confinement, as depicted by Fig. 4(a). When *D* increases further to >10 µm, no lateral confinement can be seen. An excellent illustration of this lateral confinement is shown in a curved waveguide with ~52 mm radius of curvature. For *D*~5 µm, the input is guided through the bend, shown in Fig. 4(b). As *D* increases, the input light is no longer guided. Finally, the effectiveness of lateral confinement can be seen by mode evolution with a lateral displacement between the two HCGs. As the top HCG is displaced from the bottom, the mode spreads out and finally disappears with a ~13 µm displacement, as shown in Fig. 4(c).

Optical loss is characterized for various combinations. As *D* decreases, lateral leakage decreases due to stronger confinement; on the other hand, however, the light bounces more with the HCG when propagating along the waveguide, thus increasing loss. There is an optimal *D* where minimized loss is achieved. Due to a large N.A. mismatch between the launching objective and the waveguide in our present setup, coupling loss is estimated to be ~15 dB. For a 20 mm length waveguide with *D* ~ 5.5 µm, the total loss is measured to be ~15 dB, completely dominated by the coupling loss. A more detailed loss characterization and further design optimization is underway.

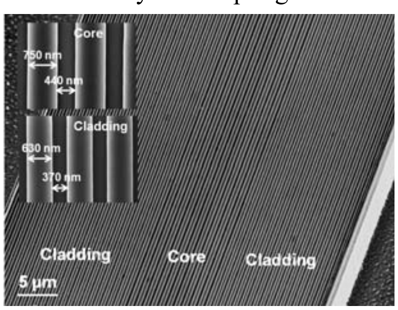

Fig. 3. SEM image of a fabricated HCG layer on SOI wafer. Core and cladding are clearly seen. Indent, zoomed-in SEM image of core and cladding region.

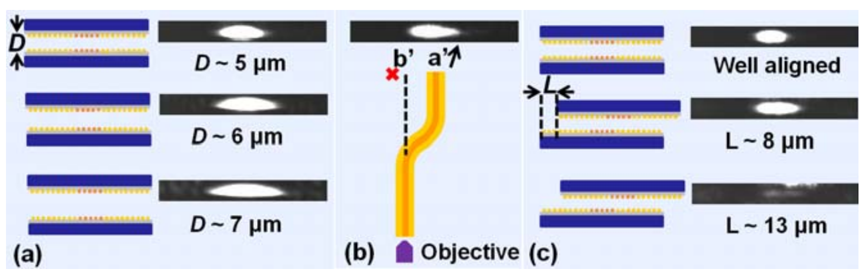

Fig. 4. Mode profiles in different alignment conditions and a curved waveguide. (a) As waveguide height *D* increases, mode is less and less confined. At *D*~7 µm, lateral leakage is severe. When *D*>~10 µm, no lateral confinement can be seen (not shown here). (b) Schematics of a curved waveguide. At *D*~5 µm, light is guided by the bend; mode profile is seen at a’ port. No light is detected at b’ port. (c) As lateral misalignment *L* increases, the mode spreads more laterally and finally disappears when *L*~13 µm. The image window is approximately 110 µm by 13 µm.

In summary, we experimentally demonstrate a new class of hollow core waveguide based on HCGs. Lateral confinement is achieved by only using two HCG planar structures. This opens up a new scheme of lateral confinement in waveguides by manipulating surface reflection phase.

Acknowledgement

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Reference

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