Novel 3D Hollow Optical Waveguide with Lateral and Vertical Periodicity for Tunable Photonic Integrated Circuits

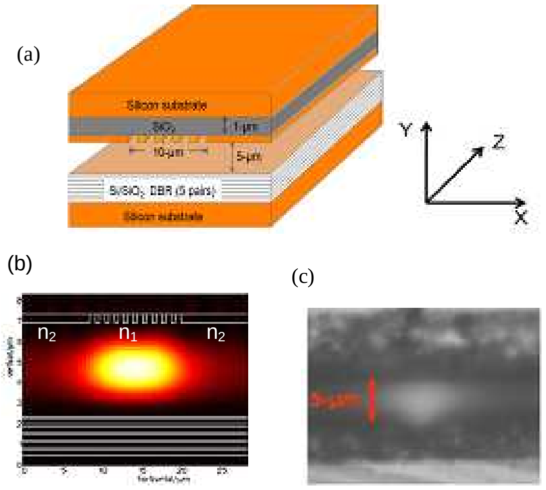
Mukesh Kumar[1], Chris Chase[2], Vadim Karagodsky[2], Takahiro Sakaguchi[1], Fumio Koyama[1] and
Connie J. Chang-Hasnain[2]
[1]Microsystem Research Center, Tokyo Institute of Technology, Japan, Email:kumar.m.aa@m.titech.ac.jp
[2]Department of Electrical Engineering and Computer Science, University of California Berkeley, USA

Abstract: A novel design-flexible 3D-hollow-waveguide with lateral- and vertical-periodicity has been demonstrated. A high-index-contrast-grating-(HCG), introduced as a lateral-periodicity, provides vertical as well as lateral-optical-confinement. The combined effect of vertical and lateral periodicity results in a low-polarization-dependence.

A tunable hollow waveguide (HWG) offers low temperature dependence and giant continuous tuning over 150 nm [1] at the same time and can be a promising candidate for temperature insensitive and tunable photonic integrated circuits. Our previous hollow waveguides consist of distributed Bragg reflectors (DBR) at the top and bottom and the light is guided in the air gap in between the two DBRs. A remaining difficulty is its large polarization dependence. The reflectivity of DBRs in HWG is highly polarization dependent because of the periodicity only in one (vertical) direction. Due to a larger field penetration into the DBRs for the TM-mode than the TE-mode, the propagation constant β_{TM} is larger than β_{TE}, hence resulting in a significant birefringence. The polarization dependence of HWG becomes very large at narrow air cores [2] where HWG offers giant tuning in propagation constant [1]. Also, we found that the polarization dependence of HWG can be reduced even for narrow air cores, if a lateral periodicity is introduced in the HWG to support the lateral polarization. A high contrast grating (HCG) based mirror can replace the DBR mirror and can provide broadband high reflection [3]. Recently, high-contrast grating hollow waveguides have been proposed to achieve extremely low loss (< 0.01 dB/m) [4]. The HCG mirror can be introduced, as a lateral periodicity, in hollow waveguides to reduce its birefringence. The combined (and opposite) effect of DBR (vertical periodicity) and HCG (lateral periodicity) provides us a reduction in polarization dependence even at narrow air cores. Important issues are how to realize low-loss 3D hollow waveguides and the design flexibility in their polarization dependence.

In this paper, we propose a 3D hollow waveguide with a DBR mirror and an HCG mirror. We show that the combination of DBR and HCG mirrors can vertically confine the light in air and can reduce the polarization dependence of the hollow waveguide. The low propagation loss and low polarization dependence have been demonstrated in theory and experiment. In particular, it is possible to achieve the 2D confinement by simply reducing the width of the HCG, which can lead to a cost-effective waveguide fabrication. The presence of HCG also increases the design flexibility of the HWG to realize other optical functionalities.

The schematic of the proposed hollow waveguide is shown in Fig. 1(a); the structure consists of a distributed Bragg reflecting (DBR) mirror at the bottom having 5 pairs of Si/SiO$_2$ and an HCG mirror at the top which consists of silicon/air grating on a standard SOI wafer. The important design parameters of the waveguide are: air core thickness *D*, grating height t_g, grating pitch Λ and grating duty cycle. The air-core thickness of the hollow waveguide is 5 µm and the grating parameters: grating height t_g, grating pitch Λ, and the duty cycle are 0.45-µm, 1.2-µm, and 0.41, respectively. For the simulation, the wavelength of 1.55 µm has been chosen. The width of grating region in the top HCG mirror is around 10-µm.



Fig, 1. (a) Schematic of 3D hollow waveguide using a DBR mirror and a high index contrast grating (HCG) mirror, (b) calculated mode-field distribution where n_1 = 0.9922, n_2 = 0.9879, $n_1 > n_2$ and (c) measured near-field profile. Z is the propagation direction.

For the implementation of hollow waveguides in practical photonic devices, it is necessary to confine light in lateral direction. 2D optical confinement in hollow waveguides can be achieved by increasing the effective index of the air core in the middle of the air core region. This can be done by introducing the HCG only in the middle region as shown in Fig. 1(b), where the effective index of the fundamental mode in the middle of an air core is n_1 while the effective index of rest of the air core is n_2. We found that the presence of an HCG increases the effective index of the fundamental guided mode causing $n_1 > n_2$, which provides strong lateral optical confinement because of the quasi-total internal reflection. Figure 1(b) shows the calculated TE-mode field distribution where we note strong vertical and lateral optical confinement. The calculated effective index n_1 under the HCG is 0.9922 while the effective index n_2 of the outside

978-3-8007-3173-2 © VDE VERLAG GMBH

region is 0.9879. Therefore 2D confinement can be realized by introducing a patterned HCG in the middle. The calculated propagation loss at $t_g = 0.45$ µm, $\Lambda = 1.2$ µm and DC = 0.41 is 2.2 dB/cm at an air-core thickness D = 5 µm, which can be further reduced by increasing the number of DBR pairs in a bottom mirror. The calculated birefringence is 5×10^{-4}, at $t_g = 0.48$ µm with $\Lambda = 1.2$ µm and DC = 0.41 at an air-core thickness D = 5 µm. It is noted that a small enough value of birefringence, 5×10^{-4}. Also, the fabrication tolerance of propagation loss as well as birefringence is large enough to withstand standard variation in grating parameters. Figure 1(c) shows the measured near field pattern where a strong vertical and lateral confinement has been observed. The calculated lateral spot size is 11-µm while the measured lateral spot size is 12-µm.

The schematic of the fabricated hollow waveguide is shown in Fig. 2(a); the structure consists of a distributed Bragg reflecting (DBR) mirror, as vertical periodicity, at the bottom having 5 pairs of Si/SiO_2 and an HCG mirror, as lateral periodicity, at the top. The bottom DBR mirror is loaded with SU-8 spacers. The quarter wavelength thick layers Si/SiO_2 (5 pairs) as a DBR mirror were deposited on a silicon substrate by electron beam evaporation. On the DBR mirror, 5 µm thick SU-8 spacers have been partly formed on the bottom DBR mirror using standard photolithography. The air-core thickness of HWG is fixed by the SU-8 spacer layer thickness on the DBR mirror. The HCG mirror on the top was formed in an SOI wafer having 1 µm thick SiO_2 and 0.45 µm thick silicon layer. The Si/air grating was fabricated by electron beam lithography followed by dry etching. The air core thickness of the hollow waveguide is 5 µm and the grating parameters: grating height t_g, grating pitch Λ, and the duty cycle are 0.45 µm, 1.2 µm, and 0.41, respectively. The bottom DBR mirror loaded with SU-8 spacers was then bonded onto the top HCG mirror to form the hollow waveguide with vertical and lateral periodicity.

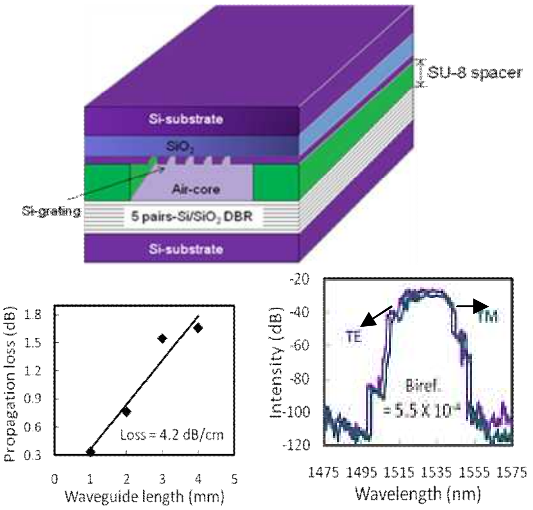


Fig. 2. (a) Schematic of fabricated 3D HWG with a patterned HCG, (b) measured propagation loss by cut-back method and (c) reflected spectrum of grating loaded HWG, grating acts as a reflecting element, showing measured birefringence. The HWG parameters are: air core thickness D = 5 µm, grating height $t_g = 0.45$ µm, grating pitch $\Lambda = 1.2$ µm, duty cycle = 0.41.

The propagation loss of the HWG has been measured using cut-back method. We prepared various lengths of hollow waveguides. The measured propagation loss versus waveguide-length is shown in Fig. 2(b). The measured propagation loss estimated from Fig. 2(b) is 4.2 dB/cm while the calculated propagation loss of the same structure is 2.2 dB/cm. The measured value of propagation loss is larger than its calculated value which may be because of the fabrication errors which may include imperfect DBR-layer thickness, imperfect HCG-parameters and/or surface roughness inside air-core.

To measure the birefringence of the HWG we additionally formed a SiO_2 grating perpendicularly to the propagation direction on the DBR mirror which acts as a reflecting element. The reflected peak (Bragg) wavelength of the grating loaded HWG is proportional to the propagation constant of the HWG fundamental mode. The birefringence, in terms of Bragg wavelength is given by $B = (\lambda_{TE} - \lambda_{TM}) / \lambda_{TE}$, where λ_{TE} and λ_{TM} are the Bragg wavelength for TE and TM fundamental modes, respectively. The measured reflected spectrum of the fabricated 3-mm long HWG with a SiO_2 grating is shown in Fig. 2(c). The central peak wavelength for TE-mode is 1527.8 nm while that for TM-mode is 1527.0 nm which corresponds to a birefringence of 5×10^{-4}, which is around 15 times smaller than that of HWG with two DBRs.

In conclusion, a 3D hollow waveguide with vertical and lateral periodicity has been demonstrated for widely tunable devices with low polarization dependence. The combination of DBR and HCG mirrors enables strong vertical and lateral confinement in air and reduced polarization dependence even at narrow air-cores. An acceptable low propagation loss for millimeter long devices has been obtained theoretically and experimentally. A reduction in HCG-width has been shown to exhibit strong lateral optical confinement. A small birefringence of the order of 10^{-4} has been demonstrated. The proposed structure can be used with narrower air-cores to realize widely tunable photonic devices with low polarization dependence and low temperature sensitivity.

Acknowledgement

This work is supported by Photonics Integration – Core Electronics (PICE) program under the Global-COE of Ministry of Education of Japan and by the Center for Integrated Access Networks (CIAN) sponsored by the National Science Foundation (NSF) USA. The authors thank Amit Lakhani for his assistance in wafer bonding and Bala Pesala for waveguide measurements and helpful discussions.

References

1. T. Miura, F. Koyama, Y. Aoki, A. Matsutani and K. Iga, Jpn. J. App. Phys. **40** (2001) L688.
2. M. Kumar, T. Sakaguchi, and F. Koyama, *Appl. Phys. Lett.* **94** (2009) 061112.
3. M. C. Y. Huang, Y. Zhou, and C. J. Chang-Hasnain, Nature Photonics **1** (2007) 119.
4. Y. Zhou, V. Karagodsky, Bala Pesala, F. G. Sedgwick, and C. J. Chang-Hasnain, Optics Express **17** (2009) 508-1517.