Propagation Characteristics of Hollow Optical Waveguide for Temperature-Insensitive Photonic Integrated Circuits

Toru Miura, Fumio Koyama, Yasuhiko Aoki, Akihiro Matsutani and Kenich Iga[*]
Microsystem Research Center, P&I Lab., Tokyo Institute of Technology
4259 Nagatsuta, Midori-ku, Yokohama, 226-8503 JAPAN
Phon. +81-45-924-5077, Fax +81-45-924-5961, E-mail: tmiura33@ms.titech.ac.jp

1. Introduction

Wavelength division multiplexing (WDM) is the key for photonic networks to meet the rapid growth of internet traffics. Passive photonic devices including optical switches, optical demultiplexers, filters and optical routers are becoming very important for future photonic networks. The dielectric waveguides have been used for guiding optical wave. But their temperature sensitivity is a remaining problem, which comes from the temperature dependence of refractive-index of material. If we are able to realize a low-loss hollow waveguide in which light can be confined in air, we can avoid this difficulty. Metallic or dielectric-coated hollow waveguides have been discussed.[2)] The use of leaky waveguiding such as an antiresonant reflecting optical waveguide (ARROW) [2)] may be a possible way to realize a hollow optical waveguide. Recently, an all-dielectric coaxial optical waveguide [3)] based on photonic bandgap was proposed and some unique features were suggested. We proposed a novel fabrication process of hollow waveguides either with metal thin film coating or with dielectric multilayer coating [7)].

In this paper, we present the fabrication and the propagation characteristic of a hollow optical waveguide with Au film coating on the walls. The disadvantage of metallic square waveguides, which are widely used in the microwave frequency region, is an absorption loss at an optical frequency. But, the result shows that the propagation loss is in an acceptable level for mm-length devices. Also, if we adopt dielectric multilayer coating on walls, we can expect low-loss and polarization- insensitive propagation characteristics. We fabricate a slab hollow optical waveguide with Au film coating. The propagation characteristic of the fabricated waveguide is presented.

2. Modeling of Hollow Waveguide

The schematic structure of the proposed hollow optical waveguide is shown in Fig. 1. The light can propagate along the waveguide by the reflection at two substrate surfaces. In order to enhance the reflectivity, we use a metal coating or dielectric multilayer reflector. The advantages of this hollow waveguide include the followings.

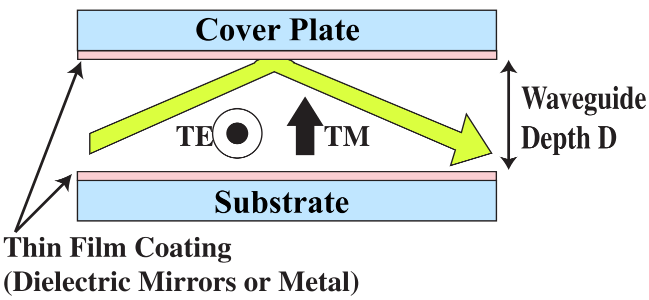

Fig.1 Hollow waveguide with thin film coating

(1) The propagation constant is almost independent of temperature when we use substrates with a low thermal expansion coefficient. The calculated temperature-sensitivity of a hallow waveguide filter for various substrates is shown in Table 1. Thus, we can realize temperature-insensitive components such as filters and demultiplexers using the hollow waveguide.

(2) We can choose any substrate, for example, Si, fused silica, GaAs, and InP. Active elements can also be

---

[*] Presently with Japan Society for the Promotion of Science / Kogakuin University
6 Ichiban-cho, Chiyoda-ku, Tokyo, 102-8471 JAPAN

integrated.

(3) Microelectro-mechanical system (MEMS) elements such as movable micromirrors can be built in the hollow waveguide for functional photonic circuits.

Table.1 Temperature Sensitivity of Hollow Waveguide Filter

	Waveguide Material	Thermal Expansion Coefficient (1/K)	Temperature-insensitivity of filter wavelength (λ=1.55μm) (nm/K)
Hollow Waveuide Filter	GaAs	9×10^{-6}	13.95×10^{-3}
	InP	5×10^{-6}	7.75×10^{-3}
	Si	3×10^{-6}	4.65×10^{-3}
	SiO_2	4×10^{-7}	6.5×10^{-4}
Conventional Waveguide Filter	InP		~ 0.1
	SiO_2		~ 0.01

As an example of this hollow waveguide photonic device, a grating demultiplexer with a hollow waveguide is shown in Fig. 2. We can expect temperature-insensitive optical demultiplexers and routers based on this concept. We estimated the propagation loss of a slab hollow optical waveguide. The loss per unit length[4)] is estimated from the reflectivity of the coated mirror and the number of reflections. The wavelength of incidence light is assumed to be *1550 nm*. The reflectivity of TE and TM modes at the incidence angle of a fundamental mode is calculated using a transfer matrix method. Also, the coupling efficiency with a single mode fiber can be estimated as a function of the depth D of the waveguide in Fig. 1. First, we calculated the propagation loss for an Au-coated hollow waveguide. The refractive index of Au was assumed to be *0.257-6.83i*. The result is shown in Fig. 3. The thickness of an Au-coated layer is *0.2 μm*. The maximum coupling efficiency with a single mode fiber is over *99 %* and the propagation losses of TE and TM modes are *0.08 dB/cm* and *3.6 dB/cm*, respectively. This result shows that low propagation loss can be realized for mm-length devices.

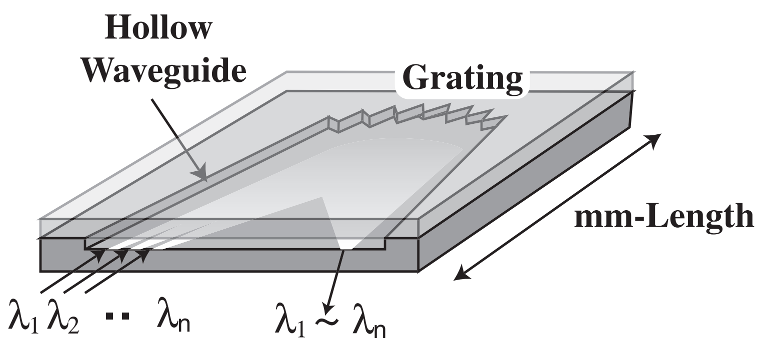

Fig.2 Temperature-Insensitive Demultiplexer

Another approach for lowering the propagation loss is also discussed. We estimate the loss using Si/SiO_2 multilayer reflectors instead of Au films. The propagation loss is calculated in the same way. The propagation loss depends on the thickness of each layer. We paid attention to the thickness of the first Si layer facing the core (air). The details

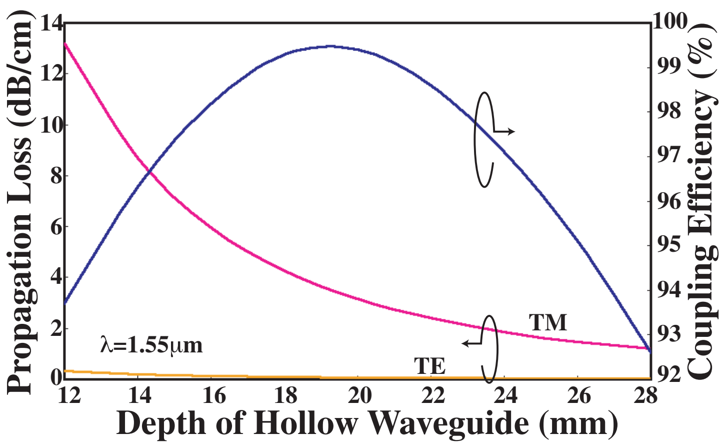

Fig. 3 Propagation Loss and Coupling Efficiency vs. Waveguide Depth

will be reported elsewhere. The relationship between the propagation loss and the thickness of the Si layer is shown in Fig. 4 for the case of four Si/SiO_2 pairs. The thickness of other layers is designed to be *λ/4* with the incidence angle θ for a fundamental mode. There is large polarization dependence, but the polarization dependence is removable by choosing an optimal Si thickness that provides the same propagation loss for the TE and TM modes. The propagation loss itself can be reduced with increasing the number of pairs. We can obtain low propagation loss without polarization dependence. For example, the propagation loss is below *0.05 dB/cm* with six pairs both for TE and TM modes.

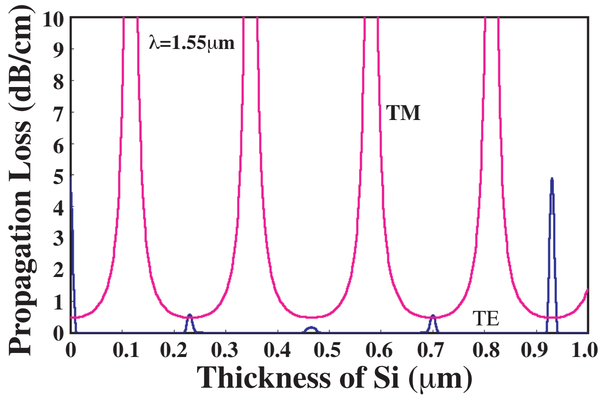

Fig.4 Propagation loss of 6 pair Si/SiO_2-coated hollow waveguide.

3. Fabrication and Experiment

We propose a simple fabrication process of a hollow waveguide. After making a deep trench, we carry out thin film coating to the substrate and planar cover plate. Then, the etched substrate is covered by the coated plate. We fabricated a hollow waveguide with Au-coated walls on a GaAs substrate. We can choose any substrate material. The waveguide pattern was formed on a GaAs substrate using photolithography followed by inductively coupled plasma etch [5)]. The etch depth was *18 μm*. Smooth and vertical etching was successfully demonstrated. Then, *0.2 μm*-thick Au was deposited on the etched substrate and another GaAs plane substrate. The two substrates were placed face to face with pressing the upper substrate mechanically. The scanning electron microscope (SEM) image of an etched waveguide is shown in Fig. 5. The width and the depth of this waveguide are *20 μm* and *18 μm*, respectively.

We measured the propagation characteristic of a slab waveguide with a waveguide width of 1 mm. The propagation characteristics of a channel waveguide are under investigation. The depth and the length of the measured waveguide were *21 μm*. The intensity profile of the input and the output light through the waveguide was measured. The wavelength is *1550 nm*. Because the contact between the two substrates was not perfect, the waveguide depth became thicker (*30 μm*) than the etched depth. The full-width at a half maximum (FWHM) of the input and the output light are *10.2 μm* and *14.4 μm*, respectively. The measured spot size is in agreement with the calculated value of *15 μm*. An important observation is that propagating light is in the fundamental mode.

The insertion loss was measured for various lengths of the hollow waveguide. The result

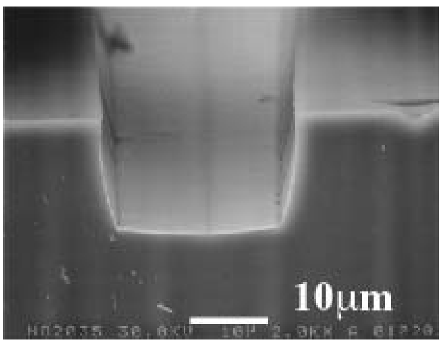

Fig.5 SEM image of deeply etched GaAs.

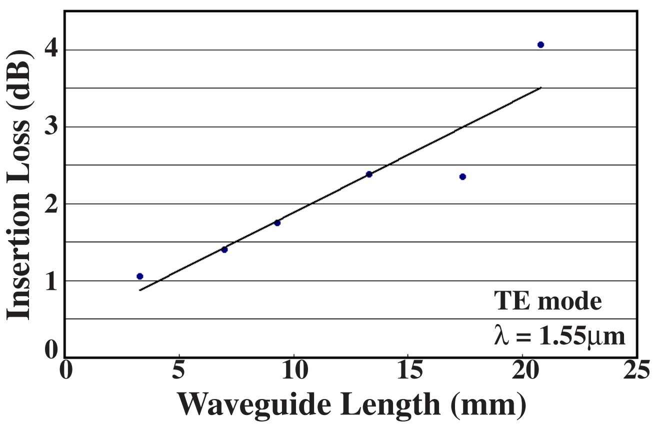

Fig.6 Insertion loss versus waveguide length.

is shown in Fig. 6. The measured propagation loss was *1.5 dB/cm* for TE mode, while the calculated propagation loss was *0.48 dB/cm* for TE mode. The higher measured loss would be due to the scattering at the etched bottom surface. This insertion loss can be reduced by improving the flatness of the etched bottom surface. The coupling loss is also estimated to be 0.5 dB from Fig. 6. A lower coupling loss with a single mode fiber can also be expected by fixing the upper plate at right position.

4. Conclusion

The modeling and fabrication of a Au-coated hollow waveguide were presnted. A reasonably low loss propagation can be obtained for Au film coated walls. Dielectric multilayer mirrors can provide lower-loss and polarization-insensitive waveguides. We can choose any kind of substrate, if we can perform a deep etch to form a hollow waveguide. We are currently working to realize temperature-insensitive optical filters and grating multiplexers using the hollow waveguide.

Acknowledgement

This study was supported by a Giant-in-Aid for COE Research from the Ministry of Education, Culture, Sports, Science and Technology (#07CE2003, "Ultra-parallel Optoelectronics").

References

1)E. A. J. Marcatili and R. A Schmeltzer: The Bell System Technical J.**43** (1964) 1783

2) M. Miyagi, A Hongo and S. Kawakami: IEEE J. Quantum Electron. QE-19(2) (1983) 136

3) Y. Kokubun, T. Baba, T. Sasaki and K. Iga: Electron. Lett. **22** (1986) 892

4) M. Ibanescu, Y. Fink, S. Fan, E.L. Thomas and J.D. Joannopoulos: SCIENCE. **289** (2000) 415

5) T. Baba, Y. kokubun, T. Sasaki and K. Iga: J. Lightwave Technol. **6** (1988) 1440

6) A. Matsutani, H. Ohtsuki, F. Koyama, and K. Iga: Jpn. J. Appl. Phys. **38** (1999) 4260

7) T. Miura, F. Koyama, Y. Aoki, A. Matstutani and K. Iga, Optical Interference Coatings, WD7 (2001)