Design and fabrication of DBR resonators for sensing devices using Nb_2O_5 horizontal slot waveguides

Nao Suzuki
Dept. of Electrical and Electronic Engineering
Kanagawa Institute of Technology
Atsugi, Kanagawa, Japan
nsuzuki23@ele.kanagawa-it.ac.jp

Yoshiki Hayama
Dept. of Electrical and Electronic Engineering
Kanagawa Institute of Technology
Atsugi, Kanagawa, Japan
yhayama@ele.kanagawa-it.ac.jp

Takumi Hinata
Dept. of Electrical and Electronic Engineering
Kanagawa Institute of Technology
Atsugi, Kanagawa, Japan

Maho Akiyama
Dept. of Electrical and Electronic Engineering
Kanagawa Institute of Technology
Atsugi, Kanagawa, Japan

Katsumi Nakatsuhara
Dept. of Electrical and Electronic Engineering
Kanagawa Institute of Technology
Atsugi, Kanagawa, Japan
knakatsu@ele.kanagawa-it.ac.jp

***Abstract*— We designed and fabricated distributed Bragg reflector (DBR) resonators structure of the Nb_2O_5 horizontal slot waveguide. Also, the hollow slot in DBR resonators and resonance characteristics were obtained in fabricated devices.**

Keywords—Horizontal slot waveguide, Niobium-oxide, hollow slot, Distributed Bragg reflector

I. INTRODUCTION

Waveguides with high-index-contrast materials have enabled the realization of ultra-small optical devices. In recent years, the sensors which composed by optical waveguides are widely studied. Typical optical sensors detects refractive index change by detection targets. The compact, high sensitive and high integrative can be realized by using waveguide-based optical sensors. Also, it has advantage for explosion proof measurement. Because of it doesn't happen sparks.

The slot waveguide structures consist of a low refractive index medium in a narrow region sandwiched between two high-refractive-index media. The electric field discontinuity at the interface between high-index-contrast materials enable the strong confinement of light inside the slot region with higher density compared with conventional optical waveguides [1]. The slot waveguides are classified into two kind of structures, one of the vertical slot waveguides, the others are horizontal slot waveguides. Vertical slot waveguides are formed it from single layer of high refractive index material. There works for TE-mode light. But, vertical slot waveguide structures requires very fine fabrication techniques. Horizontal slot waveguides are formed in the thickness direction. There works for TM-mode light. There can be formed with low roughness in slot surface by thin film thickness control [2].

In our previous work, we proposed a horizontal slot waveguide using Niobium-pent oxide (Nb_2O_5) [3]. The Nb_2O_5 material is transparent from visible to infrared. It is commonly used as an antireflection coating for camera lenses. The refractive index of Nb_2O_5 is estimated to be range of 2.1 to 2.3. It can be formed relatively low-loss waveguides. Nb_2O_5 thin films are formed by a reactive direct current (DC) sputtering system easily. Only the horizontal slot waveguides does not have wavelength characteristics, so a structure for detecting the refractive index change due to invasion of detection targets into hollow slot.

In this paper, the designed distributed Bragg reflector (DBR) resonator structure of the horizontal slot waveguide using Nb_2O_5 and fabricated DBR resonator are reported.

II. DEVICE DESIGN AND THEORETICAL CALCULATION

A schematic diagram of a Nb_2O_5 horizontal slot waveguide with distributed Bragg reflector resonator structure and cross-sectional views are shown in Fig.1 and Fig2.

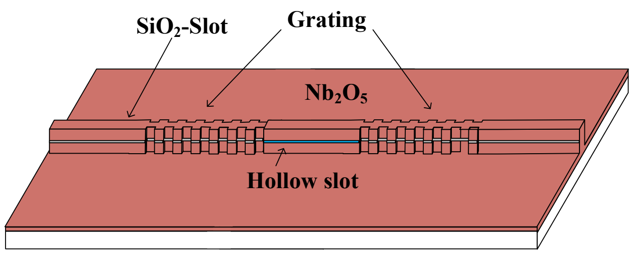


Fig. 1. Schematic of a Nb_2O_5 horizontal slot waveguide with DBR resonator structure

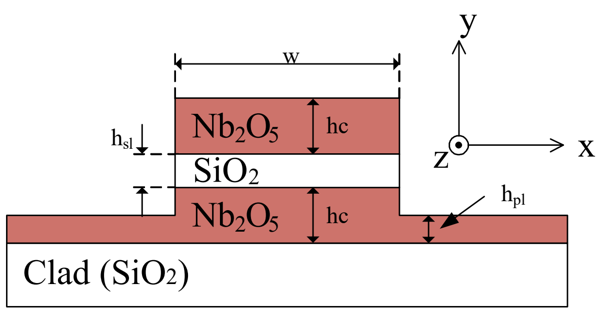


Fig. 2. Cross sectional view of a Nb_2O_5 waveguide with a horizontal slot

The structural parameters of horizontal slot waveguides for calculations are as follows: the waveguide width(w) ranges between 400(nm) to 600(nm), the slot layer thickness(h_{sl}) is 20(nm), and the thickness of the high refractive material layer at the top and bottom of the slot layer(h_c) is equal to 400[nm].

The planar serves as a protection against the undercut of the lower cladding (SiO_2 layer). The planar layer thickness(h_{pl}) is 100(nm). The high refractive index medium is Nb_2O_5 materials, which can be deposited by the reactive DC sputtering system. The refractive index of each material in the theoretical calculation was assumed as follows: Nb_2O_5 is 2.23, SiO_2 is 1.44, Air is 1.00.

DBR resonator consists of a straight waveguide sandwiched between two grating waveguides. DBR resonators have wavelength characteristics with periodic resonance peaks in stop-band. The effective refractive index of the slot waveguide is changed by filling the hollow slot formed in the cavity with the substance to be detected, thereby shifting the resonance peak. The light incident on the waveguide DBR resonator is partially reflected on the output side and returns. The optical path difference is a round trip of cavity length (L_c). Thus, the phase difference ϕ is shown Eq.(1).

$$\phi = \frac{4\pi}{\lambda} n_{eff} L_C \qquad (1)$$

When $\phi=2m\pi$ in Eq.(1) is satisfied, the light are in phase on the output side, and thus strengthen each other. Thus, the bragg wavelength (λ_B) using the effective refractive index n_{eff} is shown Eq.(2). The wavelength is defined as λ. Also, grating period is defined as Λ.

$$\lambda_B = \frac{2N_{eff}\Lambda}{m} \ (m = 1,2,3,\cdots) \qquad (2)$$

Diffraction order is defined as m. The free spectral range (FSR) is shown Eq.(3) from difference in resonant wavelength between m and $m+1$.

$$FSR = \lambda_{m+1} - \lambda_m = \frac{2}{m(m+1)} n_{eff} L_C \ (m = 1,2,3,\cdots) \qquad (3)$$

L_c is obtained from Eq.(4) by Eq.(2) and Eq.(3).

$$L_C = \frac{\lambda_m(\lambda_m - FSR)}{2n_{eff}FSR} \qquad (4)$$

L_c and Λ were designed for the waveguide widths listed in Table I. The grating depth (d) was designed 80(nm).

TABLE I. PARAMETERS FOR DBR RESONATORS WERE DESIGNED

w(nm)	400	500	600
L_c(nm)	84	95	104
L_g(nm)	58	52.5	48
Λ(nm)	439	425	415

The upper cladding assumes the use of PMMA, and theoretical calculations assume its refractive index to be 1.48 [4].

Figure3 shows the dependence of Bragg wavelength (λ_B) as a function of waveguide width (w). grating length (Λ) is defined as 425(nm).

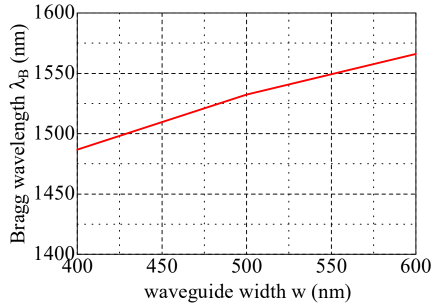


Fig. 3. Dependence of λ_B on w

Bragg wavelength (λ_B) increases by 40[nm] for an increase in waveguide width (w) of 100(nm).

Figure4 shows the dependence of λ_B as a function of grating length (Λ). waveguide width (w) is defined as 500(nm).

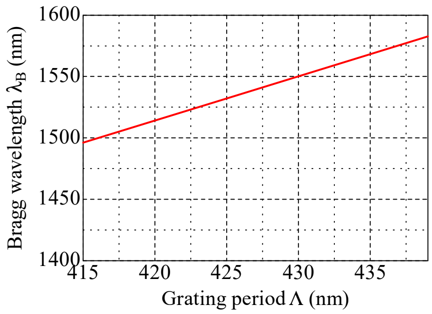


Fig. 4. Dependence of λ_B on Λ

Bragg wavelength (λ_B) increases by 36(nm) for an increase in grating length (Λ) of 10(nm).

Figure5 shows the change of FSR when L_c is changed. waveguide width (w) is defined as 500(nm). Also, grating length (Λ) is defined as 425(nm).

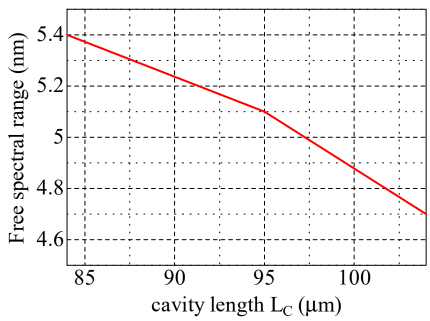


Fig. 5. Dependence of FSR on L_c

FSR decreases by 0.35(nm) for an increase in L_c of 10(nm).

III. FABRICATION AND MEASUREMENT

The proposed a horizontal slot waveguide with DBR resonator can be fabricated by the processes shown in Fig.6.

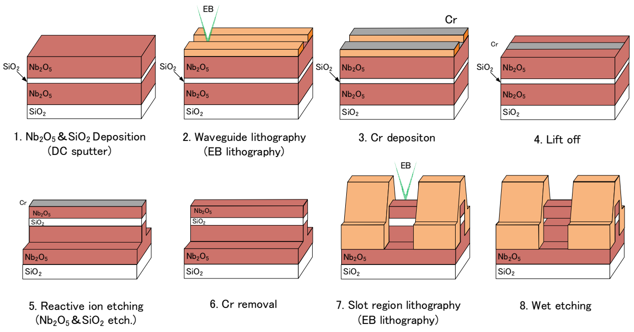
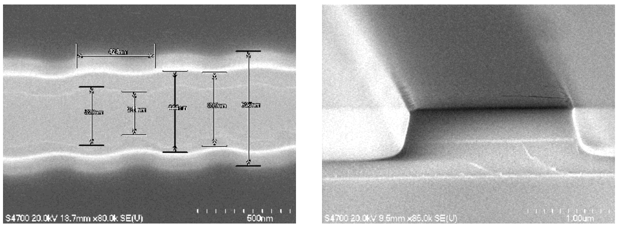


Fig. 6. The fabrication process of Nb_2O_5 horizontal slot waveguides

Lower Nb_2O_5 layers and a slot layer of SiO_2 are deposited on a Si-substrate with a thermal oxide film by using a reactive DC sputtering (SHOWA SHINKU SPS-208CW). The pattern of the waveguides with grating is formed by electron beam (EB)-lithography (CRESTEC CABL-9200TFTN) and lift-off process. The waveguides were formed by reactive ion etching (RIE). The scanning electron microscope (SEM) images of the waveguides were shown Fig.7. The parameters of the etching are the composition of etching gas as CF_4 and Ar, the flow ratio of the etching gas as CF_4:Ar=8:2(sccm), gas pressure as 6(Pa), and RF power as 100(W). The Λ is 424(nm) , the d is 45(nm) were obtained.



(a) w=500(nm) (b) w=2(μm)

Fig. 7. after etching image

The hollow slots were formed using an EB resist (OEBR1000 from Tokyo Ohka) as the upper clad material. EB resist has good waveguide coverage and it has selectivity in wet etching with hydrofluoric acid (HF). After drawing the area for the hollow slot in the center of this waveguide by EB lithography, the hollow slot area was formed by selective wet etching of SiO_2 with HF for 3(min). The etching rate of SiO_2 between the Nb_2O_5 layers was 248.4(nm/min) in a previous study [5]. The SEM images after formed hollow slots shown in Fig.8. The pattern of the hollow slot region formed 2(μm) by EB lithography. The hollow slot region is 1.7(um) was obtained.

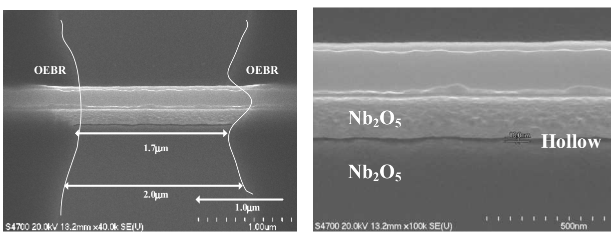


Fig. 8. Hollow slot image

The wavelength characteristics of after formed hollow slots was shown in Fig.9. The FSR is 4.2(nm), stop band width is 15.4(nm) were obtained.

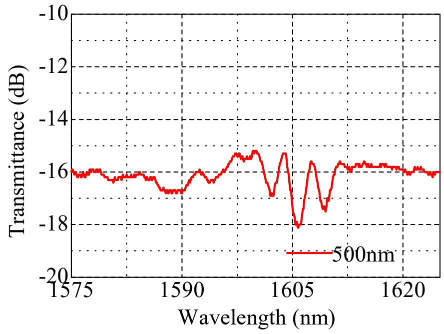


Fig. 9. The wavelength characteristics after formed hollow slot

Table Ⅱ shows the comparison between the measured results and the theoretical calculations.

TABLE Ⅱ. COMPARISON OF THEORETICAL ANALYSIS AND MEASUREMENT RESULTS

	FSR(nm)	Stop band width(nm)	Extinction ratio(dB)
Theoretical caluculation	4.8	18.6	10.8
Measurement result	4.2	15.4	2.8

The measured FSR was 0.6(nm) shorter than the theoretical one. This reason is that the hollow slot section has become shorter than the design. The stop band width was 3.2(nm) narrower than the theoretical wavelength. The extinction ratio was 8(dB) smaller than the theoretical wavelength. These reasons are that the grating coupling ratio lower than the design.

IV. CONCLUSION

We designed and fabricated DBR resonator of the horizontal slot waveguide using Nb_2O_5. Furthermore, hollow slots were formed in the cavity, and wavelength characteristics were measured. The fabricated devices have resonance characteristics due to the hollow slots. We are currently working on improving devices for demonstration of sensing operations.

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REFERENCES

[1] V. R. Almeida, et al, Opt. Lett., vol. 29, no. 11, pp. 1209(2004).
[2] N. -N. Feng, et al, IEEE J. Quantum Electron., vol. 42, no. 9, pp. 885 (2006).
[3] Yoshiki Hayama, et al, Proc. of 23rd MOC, pp. 44.
[4] Huagang Lin,et al, vol. 30, no. 12, pp. 3 (2022)
[5] Y. Hayama et al, IEICE TRANS. ELECTRON., vol. E103-C, no.11, pp. 669-678(2020).