Zr-doped Silica-based Planar Lightwave Circuits with High Resistance against Blue Light

Yuji Fujiwara[1], Junji Sakamoto[1], Toshikazu Hashimoto[1] and Kei Watanabe[1]

yuji.fujiwara.vu@hco.ntt.co.jp
[1]NTT Device Technology Labs, NTT Corporation, 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-0198, Japan

Keywords: Planer lightwave circuits, Smart glass, Zirconium oxide

ABSTRACT

To expand applications of PLCs, we investigated the resistance of Zr-doped PLCs against high-power blue laser light. Zr-doped PLCs showed effective refractive index change of less than 1/10 of that of conventional PLCs. It is small enough for practical use, which requires over 10 mW blue light.

1 Introduction

Due to the prohibition of overseas and domestic movement caused by COVID19, compact displays such as smart glasses are attracting attention [1-3] because they enable hands-free sharing of video and support operation in remote areas, with potential to user in new styles of work, and education. These displays often incorporate a laser diode (LD) projector system. In this system, micro bulk optics such as dichroic mirrors and micro lenses combine LD beams of the three primary colors [red (R), green (G) and blue (B)] into a single RGB beam. Then, the RGB beam are incident on a micro electro mechanical systems (MEMS) mirror [4]. However, the micro bulk optics prevent us from reducing assembly cost and constructing more compact displays. To solve these problems, an LD projector system has recently been developed that uses silica-based planar lightwave circuits (PLCs) instead of micro bulk optics [5,6]. PLCs are generally configured with germanium (Ge)-doped silica as the core like in optical fibers, and they can be widely used in the telecommunications systems and are mass-producible. By using these PLCs as combiners, the laser beams of the three colors from LDs can be directly coupled into them. Therefore, the number of optical parts and assembly cost can be reduced dramatically. Moreover, they can provide a more compact display. Although the PLC combiner is one of the most promising solutions, their propagation loss increases and their refractive index changes when light with shorter high-power wavelengths like those of blue/green light are incident. This degradation is attributed to a color center formed by breaking Si-Ge and Ge-Ge bonds with incidence of high-energy light such as blue and green [7,8].

Here, to suppress the degradation due to the light with shorter wavelengths, we propose zirconium (Zr)-doped PLCs for high-power blue light application. Zr-doped PLCs are already used as high-contrast PLCs in telecommunications applications [9], but whether they are resistant to high power blue light has not been investigated yet. We fabricated Zr-doped PLCs, and measured their effective refractive index change caused by incident high-power blue light to investigate their resistance against it.

2 Sample Preparation and Measurement

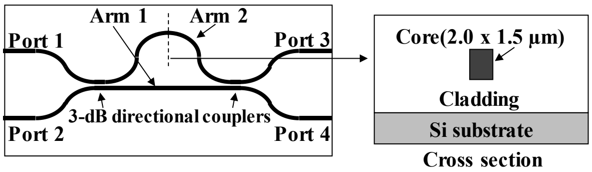

Fig. 1 MZI configuration

To investigate the resistance of Zr-doped PLCs against high-power blue light, we fabricated a Mach-Zehnder interferometers (MZIs) as test circuits as shown in Fig. 1. The PLCs were fabricated on a Si substrate using a conventional process [10]. The MZIs consist of a pair of 3-dB directional couplers and arm waveguides (arm 1 and 2) with different lengths (ΔL=54 µm). The core is 2.0 µm high and 1.5 µm wide. The refractive index difference (Δn) between the core and cladding was set to 1.1%. For comparison, Ge-doped samples with different dopant concentrations were also prepared but with the same design, core dimensions, and Δn. The concentrations of Zr and Ge in the respective samples were 1.9 at.% and 4.7 at.%, measured by energy dispersive X-ray spectroscopy (EDS).

The resistance against high-power blue light was evaluated by measuring the amount of wavelength shift in the transmission spectra of the MZIs. The measurement procedure with the measurement setup shown in Fig. 2 was as follows. First, we measured the initial spectrum for each sample. White light from a super continuum light source was input from port 1 as incident light, and the output from port 4 was measured by an optical spectrum analyzer with an attached multi-mode fiber. Then, to investigate the resistance of the PLCs against high-power blue laser light, blue light with a 445-nm wavelength from an LD was incident to port 2 for about 200 h. Incident power was adjusted so that each Zr- and Ge-doped sample had different output powers of 0, 10, 20, and 30 mW.

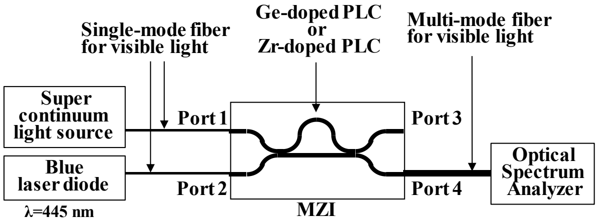

Fig. 2 Measurement setup

Here, an output power of 0 mW means that no light was incident to the samples. After that, we measured the spectra of the samples again and repeated these procedures for up to about 200 h. Note here that we designed the two directional couplers to have a very low coupling ratio at shorter wavelengths, namely that of blue light. Because the blue light propagated only to arm 1, photo-induced degradation mainly occurred in arm 1.

3 Results and Discussion

Figure 3(a) and (b) shows normalized MZI spectra of Ge- and Zr-doped PLCs between 620 and 640 nm after irradiation for 20 and 40 h. For the Ge-doped MZI in Fig. 3(a), spectral shifts can be clearly seen. On the other hand, Zr-doped MZI exhibited only slight spectral shifts as shown in Fig. 3(b). Note here that the extinction ratios of the Ge- and Zr-doped MZIs are different. This is caused by the non-optimized coupler. However, since we are concerned with the amount of spectral shift, their extinction rations do not matter here. In both the Ge- and Zr-doped PLCs shown in Fig. 3, the loss of the MZIs was almost the same before and after irradiation. Although not shown here, it was the same up to 200 h. Figure 4 shows the amount of spectral shift per hour for both the Ge- and Zr-doped MZIs as a function of output power. The vertical axis shows the amount of spectral shift per hour, because it is proportional to time. The spectral shift of Ge-doped PLCs rapidly increases with increasing output power. Thus, conventional Ge-doped PLCs can be used in low-power applications such as retinal projection but not in an application requiring over a few milliwatts of output power. On the other hand, the shifts for Zr-doped PLCs are much smaller than that for the Ge-doped ones. Even when the incident power was 30 mW, the amount of shift for the Zr-doped sample was less than 0.0027 nm/h, or less than 1/14 of that of the Ge doped one.

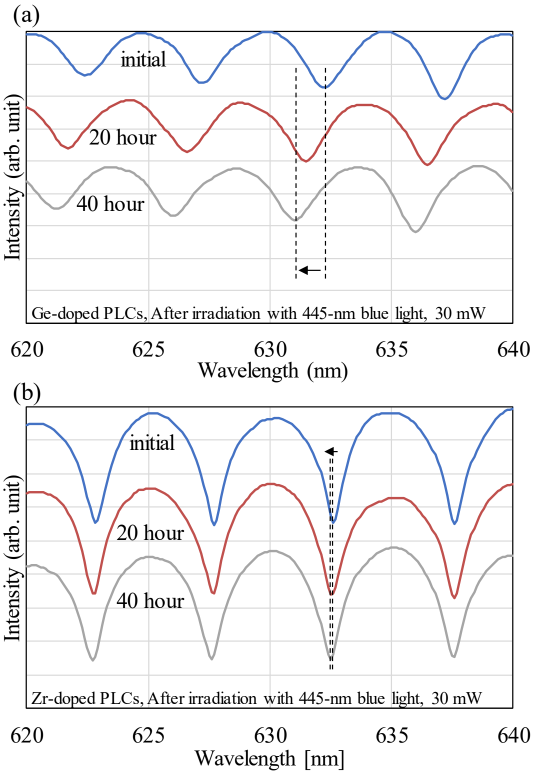

Fig. 3 Normalized MZI spectra of (a) Ge-doped and (b) Zr-doped PLCs

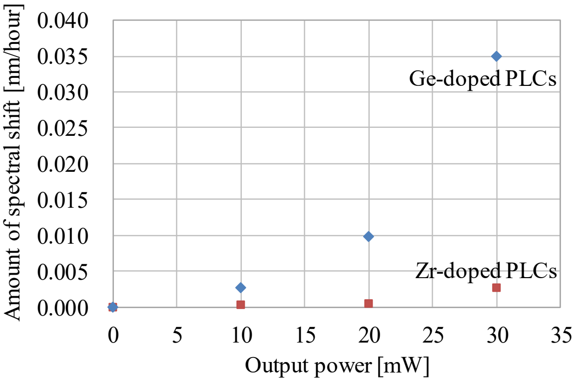

Fig. 4 Amount of spectra shift of Ge and Zr doped MZIs

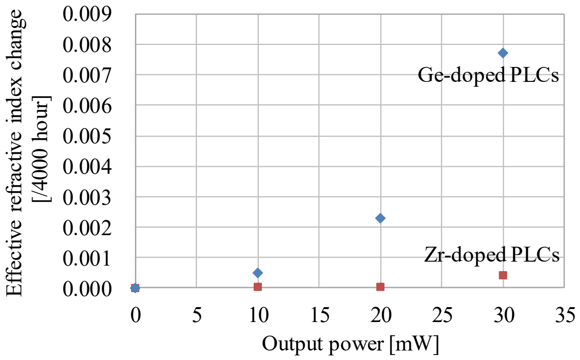

Fig. 5 Change of effective refractive index

Figure 5 shows the estimation of effective refractive index change converted from the amount of spectral shift in Fig. 4. In this estimation, it is assumed that the effective refractive index changes proportionally up to 4000 h. As one example, when we set the criteria of the refractive index's changing 5 x 10^{-4} for 4000 h, Fig. 5 indicates that Zr-doped PLCs can be used in applications requiring 20 mW. These results represent the first direct proof that Zr-doped PLCs have more ten times higher resistance than Ge-doped ones against high-power blue light.

One of the reasons Zr-doped PLCs show such high resistance against high-power blue light is the concentration of the dopants—it is lower than that of Ge-doped ones with the same Δn. It is very well known that non-doped silica has strong resistance against high-power blue light [11]. Therefore, it is employed as the core material of optical fibers used in the visible light region, which includes blue light. A lower concentration of dopant means the material characteristics approach those of non-doped silica. There may be other reasons related to, for instance, band gaps and ultraviolet absorption edge, but this is not completely understood at present. To obtain PLCs with higher resistance against high-power blue light, further studies are needed.

4 Conclusion

To expand applications of PLCs, we investigated the resistance of Zr-doped PLCs against high-power blue laser light. By measuring the spectral shifts of MZIs after irradiation with blue light for 200 h and comparing the shifts for conventional Ge-doped and the proposed Zr-doped PLCs, we demonstrated that the spectral shift for Zr- doped PLCs is less than 1/14 of that of Ge-doped ones. The evaluated refractive index change is small enough for practical use, which requires power of over 10 mW. To our knowledge, this is a first report showing that Zr-doped PLCs have high resistance against high-power blue light.

References

[1] M. Nasajpour, S. Pouriyeh, R. M. Parizi, M. Dorodchi, M. Valero and H. R. Arabnia, "Internet of Things for Current COVID-19 and Future Pandemics: an Exploratory Study," *J. Healthc. Inform. Res.*, vol. 4, pp. 325-364, (2020).

[2] S. Kim, M. A. Nussbaum and J. L. Gabbar, "Augmented Reality "Smart Glasses" in the Workplace: Industry Perspectives and Challenges for Worker Safety and Health," *IIE Transactions on Occupational Ergonomics and Human Factors*, vol. 4 no. 4, pp. 253-258, (2016).

[3] S. Kyung Kim, H. Yoon, C. Shin, J. Choi and Y. Lee, "Design and Implementation of a Smart Glass Application for XR Assisted Training of Core Nursing Skills," *J. Multimed. Inf. Syst.*, vol. 7 no. 4, pp. 277-280, (2020).

[4] N. Primerov, J. Ojeda, S. Gloor, N. Matuschek, M. Rossetti, A. Castiglia, M. Malinverni, M. Duelk, and C. Velez, "Ultracompact RGB laser diode module for near-to-eye displays," in *Proc. SPIE 11788, Digital Optical Technologies 2021*, (2021), p. 117880Q.

[5] J. Sakamoto, S. Katayose, K. Watanabe, M. Itoh and T. Hashimoto, "High-efficiency multiple-light-source red-green-blue power combiner with optical waveguide mode coupling technique," in *Proc. Of SPIE 10126*, (2017), p. 101260M-7.

[6] J. Kamei, "Compact Full Color Optical Engine for Smart Glasses," in *Proc. SPIE 11764, SPIE AVR21 Industry Talks II*, (2021), p. 117641E.

[7] P. St.J. Russell, D. P. Hand, Y. Chow, and L. J. Poyntz-Wright, "Optically induced creation, transformation, and organization of defects and color centers in optical fibers," in *Proc. SPIE 1516, International Workshop on Photoinduced Self-Organization Effects in Optical Fiber*, (1991), pp. 47-54.

[8] Y. Fujiwara, J. Sakamoto and K. Watanabe, "Blue/green-light resistant non-doped silica waveguide for visible-light application," in *Proc. Microoptics Conference (MOC) 26th*, accepted, (2021).

[9] Y. Uchida, S. Yamasaki, M. Takahashi, J. Hasegawa, and T. Yagi, "Ultra-Compact 8-Arrayed 8×1 Switch Consists of ZrO2-SiO2-Based High ΔPLC," in *Proc. Optical Fiber Communication Conference*, (2015), p. W2A.11.

[10] H. Takahashi, "Recent progress on planar lightwave circuit technology for optical communication," in *Proc. 2009 Asia Communications and Photonics conference and Exhibition (ACP),* (2009), pp. 1-6.

[11] S. Unger, J. Kirchhof, S. Schroeter and A. Schwuchow, "Transmission behavior of silica core: fluorine-doped cladding fibers in the visible and ultraviolet region," in *Proc. SPIE 4616, Optical Fibers and Sensors for Medical Applications II*, (2002).