S. Yliniemi, J. Albert, A. Laronche, J. M. Castro, D. Geraghty, and S. Honkanen, Negligible birefringence in dual-mode ion-exchanged glass waveguide gratings, Applied Optics 45, 6602-6606 (2006).

# Negligible birefringence in dual-mode ion-exchanged glass waveguide gratings

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Polarization dependence of UV-written Bragg gratings in buried ion-exchanged glass waveguides is investigated. A polarization-dependent shift in Bragg wavelength of less than 0.02 nm is measured, both for the even and the odd modes of a laterally dual-mode waveguide. The measured wavelength shift corresponds to a waveguide birefringence of the order of $10^{-5}$, which is negligible for most applications in optical communications. It is observed that the UV-induced birefringence is small, within the limits of the measurement accuracy. The thermal stability of the fabricated gratings is also very good. The results are of particular importance for devices considered here since they require a polarization-independent mode-converting waveguide Bragg grating. Polarization-independent performance of these gratings enables the fabrication of a new class of integrated optical devices for telecommunication applications. © 2006 Optical Society of America

*OCIS codes:* 130.0130, 230.7380, 260.1440, 050.2770, 260.7190.

## 1. Introduction

Dense wavelength division multiplexing, in which the transmission capacity of a single optical fiber is multiplied by using several wavelengths, is a well-established key technology in telecommunication backbone and metropolitan-area networks. However, there is still a rapidly growing demand to increase the speed and flexibility of fiber-optic networks. A promising solution to meet the future requirements is to add various all-optical functionalities and devices to network subsystems.[1,2] These all-optical devices eliminate the need for optical-to-electronic conversion, the so-called electronic bottleneck. Integrated optics, which uses fabrication technologies similar to the semiconductor industry, will be critical for increasing the device manufacturability to the point where new optical solutions are both competitive with state-of-the-art existing technologies and affordable for the end user. In view of this, we have recently proposed a class of planar devices that is based on ion-exchanged glass waveguide mode splitters–combiners and mode-converting waveguide Bragg gratings. These devices include an add–drop wavelength filter,[3] a (tunable) dispersion compensator,[4] and an all-optical packet header recognition chip.[5] All these devices are composed of adiabatic asymmetric Y branches, which have waveguides of different widths, and UV-written waveguide gratings in a dual-mode waveguide.

A key requirement for the devices mentioned in the preceding paragraph is a polarization-independent operation; it is far more difficult to achieve compared to typical integrated optic devices operating solely with the fundamental mode. Most importantly, the waveguide birefringence has to be low in a relatively wide dual-mode waveguide, not only for the fundamental mode (even mode), but also for the second lateral mode (odd mode). Higher birefringence is expected for the odd mode, since it is less confined, and therefore more sensitive to the planar top interface that introduces waveguide form birefringence. Usually UV exposure induces some birefringence on devices.[6] In our case, however, the UV-written grating must not induce much birefringence. The polarization-independent operation would be difficult to achieve with other media for integrated optics,

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Received 3 January 2006; revised 27 March 2006; accepted 3 April 2006; posted 10 April 2006 (Doc. ID 66977).
0003-6935/06/256602-05$15.00/0

such as silica on silicon, although birefringence issues have more or less been solved for single-mode waveguides. With the silica-on-silicon platform, low birefringence is usually obtained by stress tailoring of the cladding layers or by UV trimming resulting in waveguide birefringence of the order of $10^{-5}$.[7] With direct UV writing, values as low as $5 \times 10^{-6}$ have been reported.[8] However, silica-on-silicon platforms typically cannot result in nonbirefringent waveguides of different widths.[9] We have recently shown that the fundamental mode of ion-exchanged waveguides can have very low birefringence for waveguides with widely varying widths.[10] Values of the order of $10^{-6}$ were measured when the burial process was followed by thermal annealing. However, we were not able to measure the birefringence for the odd mode and no waveguide grating was included. It is worth mentioning that our add–drop device showed an unacceptably large shift of about 0.25 nm in Bragg wavelength for the two polarizations.[3]

In this paper we show that a polarization-dependent Bragg wavelength shift of less than 0.02 nm, for both the even and the odd modes, is achievable in buried ion-exchanged glass waveguides with UV-written Bragg gratings. The measured values correspond to a waveguide birefringence of the order of $10^{-5}$ or below, which indicates that the UV writing does not significantly increase the waveguide birefringence. It is also observed that an UV-written Bragg grating does not significantly increase the waveguide birefringence. The paper is organized as follows: First, in Section 2 we briefly describe the waveguide and the grating fabrication method. In Sections 3 and 4 we present, respectively, the even and odd mode characterization technique and the results. Finally, in Section 5, we present our results.

## 2. Fabrication

Waveguides with mask opening widths from 2 to 5 μm were constructed in BGG31 glass by $Ag^+$–$Na^+$ ion exchange. Surface-channel waveguides fabricated in this way were then buried below the glass surface to reduce propagation losses and to obtain circular waveguides matching well with fibers. The burial was done for 2400 s at $T = 250$ °C with an applied field of 640 V/mm. The burial process also significantly reduces the birefringence by reshaping the index profile. After the burial, the sample was annealed for 105 min at 230 °C to further reduce birefringence. The waveguide fabrication process has been described in more detail elsewhere.[10,11]

After waveguide fabrication, both weak and strong Bragg gratings with a length of 7 mm were exposed into the waveguides with a pulsed ArF excimer laser at 100 pps with a pulse energy of 80 mJ. In the preliminary experiments, it was observed that the grating strength saturated after 8 min of exposure with a reflectivity of 60%. This was chosen to be the exposure time for the strong grating, while the weak grating was exposed for only 4 min resulting in a reflectivity of 40%. The phase-mask period of 1065 nm produced a Bragg grating with a periodicity of 532.5 nm into the waveguides.

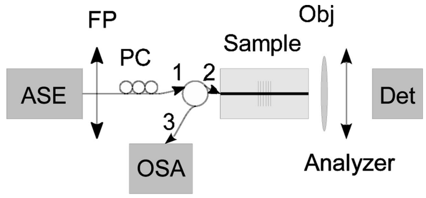


Fig. 1. Measurement setup for determining the polarization-dependent wavelength shift of the channel waveguide Bragg gratings for the even and the odd modes. An amplified spontaneous emission (ASE) source is coupled to the waveguide through a fiber polarizer (FP), a polarization controller (PC), and a circulator. The reflected light is guided through the circulator to the OSA. The setup also includes a free-space rotatable analyzer and an InGaAs detector to minimize the power in the unwanted polarization state by monitoring the transmitted light.

## 3. Characterization

An UV-exposed grating allows the measurement of the polarization-dependent wavelength (PDW) shift of the reflected light for different modes propagating in a channel waveguide. Each mode has a characteristic effective refractive index, and therefore they are reflected at slightly different wavelengths according to the Bragg condition

$$\lambda = 2n_{\mathrm{eff}}\Lambda, \tag{1}$$

where λ is the reflected wavelength, Λ is the period of the Bragg grating, and $n_{\mathrm{eff}}$ is the effective refractive index of the mode. The modal birefringence, therefore, appears as a PDW shift.

The reflected wavelengths for different modes were measured using a setup presented in Fig. 1. A broadband light source is used to simultaneously excite the modes supported by a waveguide. A fiber circulator couples the light source to the waveguide through ports 1 and 2, and the reflected spectrum is connected to the optical spectrum analyzer (OSA) through port 3. A fiber polarizer is used to selectively couple either the quasi-TE or TM polarization state to the waveguide. The power in the unwanted polarization state is minimized by monitoring the transmitted power in this polarization state, while tuning the polarization controller, as can be seen from Fig. 1. The PDW shift is the wavelength difference between the quasi-TE-mode and the TM-mode reflection peaks. For each mode, the corresponding waveguide birefringence, $\Delta n_{\mathrm{eff}}$, can be derived from Eq. (1) as

$$\Delta n_{\mathrm{eff}} = \frac{\Delta\lambda}{2\Lambda}, \tag{2}$$

where $\Delta\lambda = \lambda_{\mathrm{TE}} - \lambda_{\mathrm{TM}}$ is the measured PDW shift, and Λ is the period of the Bragg grating. The accuracy of this method is restricted by the OSA resolution and the wavelength repeatability. According to the manufacturer, the OSA (Ando Model AQ6317) used in these measurements has a resolution of 0.015 nm or

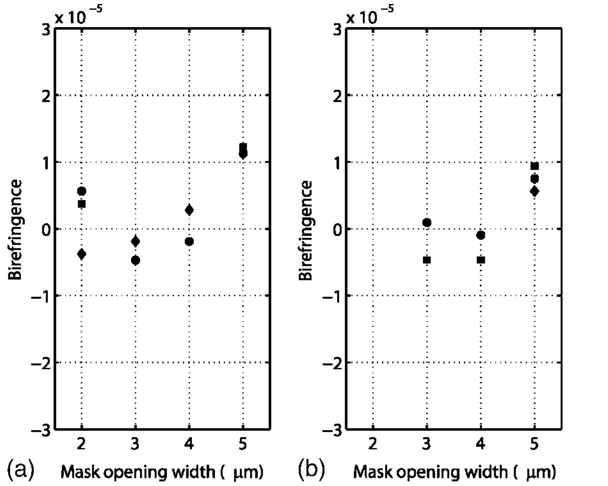


Fig. 2. Measured birefringence ($n_{TE} - n_{TM}$) from a waveguide with a weak grating for (a) the even and (b) the odd modes. Circles, squares, and diamonds refer to different measurements from waveguides with the same mask opening width.

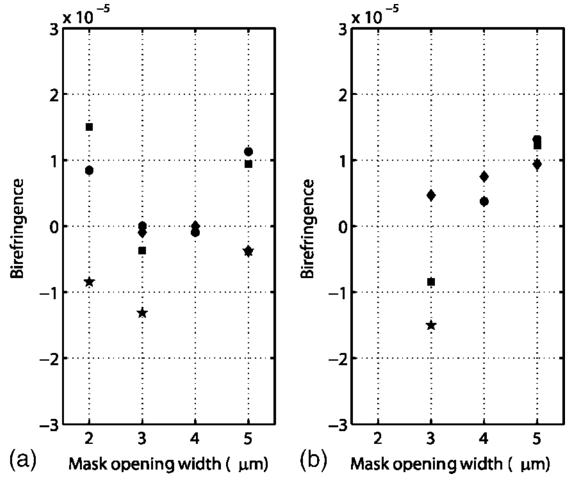


Fig. 3. Measured birefringence ($n_{TE} - n_{TM}$) from a waveguide with a strong grating for (a) the even and (b) the odd modes. Circles, squares, diamonds, and stars refer to different measurements from waveguides with the same mask opening width.

better and a wavelength repeatability of 0.005 nm. This sums up to a minimum detectable PDW shift of 0.020 nm or better, which corresponds to a birefringence of $2 \times 10^{-5}$. This value of birefringence is low enough for most telecommunications applications.

In a dual-mode waveguide, coupling from an even to an odd mode or vice versa becomes possible if the grating is slightly tilted.[12] This mode conversion occurs at a wavelength $\lambda_{eo}$ given by

$$\lambda_{eo} = \Lambda_z[n_{eff}(0) + n_{eff}(1)], \quad (3)$$

where $\Lambda_z$ is the period of the grating in the propagation direction, and $n_{eff}(0)$ and $n_{eff}(1)$ refer to the even- and the odd-mode effective refractive indices. In our proposed devices the grating is purposely positioned at an angle to obtain the even–odd (or odd–even) mode conversion. The grating angle should be optimized to maximize the mode conversion in reflection.[12]

## 4. Results

The waveguide birefringence for the even and odd modes as a function of a mask opening width is presented in Figs. 2 and 3, Fig. 2 referring to the measured birefringence with the weak grating and Fig. 3 referring to the measured birefringence with the strong grating. In all the waveguides, the variation in birefringence for a given waveguide width is less than the measurement resolution, which is $2 \times 10^{-5}$. The birefringence of the strong grating appears to be slightly larger than that of the weak grating, which indicates that some birefringence is induced by the UV writing. This is not conclusive, however, since all the values are below the OSA accuracy limit. Nevertheless, the measured values of birefringence are negligible for most applications, corresponding to a PDW shift of less than 0.02 nm. In most practical applications, reflectivities approaching 100% are required. This can be achieved by increasing the grating length from 7 to approximately 12 mm. This would not increase the PDW shift, since birefringence is a local effect independent of the grating length.

Figures 4(a) and 4(b) present typical reflection spectra obtained from waveguides, respectively, with mask opening widths of 2 and 5 μm for both polarizations. The reflection spectra for the quasi-TE and TM modes overlap within the measurement accuracy of 0.02 nm. The waveguide with a mask opening width of 2 μm is single mode with a Bragg wavelength of 1549.11 nm (corresponding to an effective refractive index of 1.455). For a waveguide with a mask opening width of 5 μm, both the even and the odd modes can be observed at Bragg wavelengths of 1550.06 nm (1.456) and 1548.49 nm (1.454), respectively. In the wider waveguide, a third reflection peak is observed between the even and the odd modes. The Bragg wavelength (1549.25 nm) was calculated to match the wavelength obtained from Eq. (3), confirm-

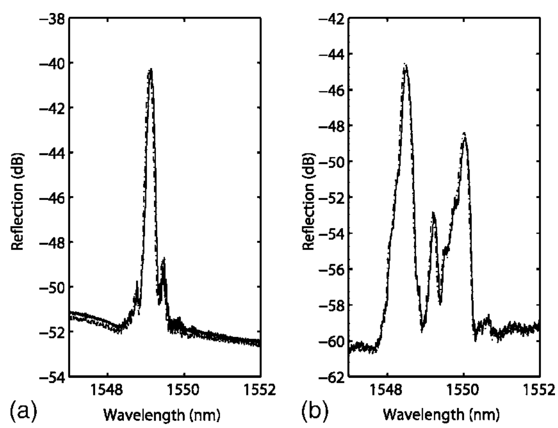


Fig. 4. Reflection spectrum for a waveguide with a mask opening width of (a) 2 μm and (b) 5 μm. The solid curve refers to the quasi-TE-polarization state and the dashed–dotted curve to the quasi-TM-polarization state.

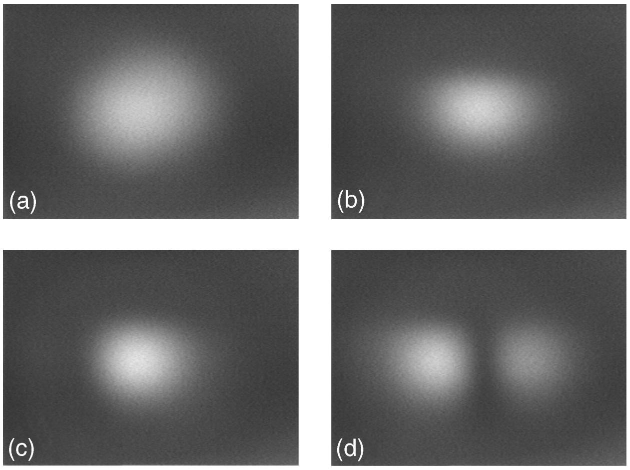


Fig. 5. Mode intensity profiles (a) for a single-mode fiber, and for waveguides with mask opening widths, (b) 2 μm (single mode), (c) 5 μm (even mode), and (d) 5 μm (predominantly odd mode).

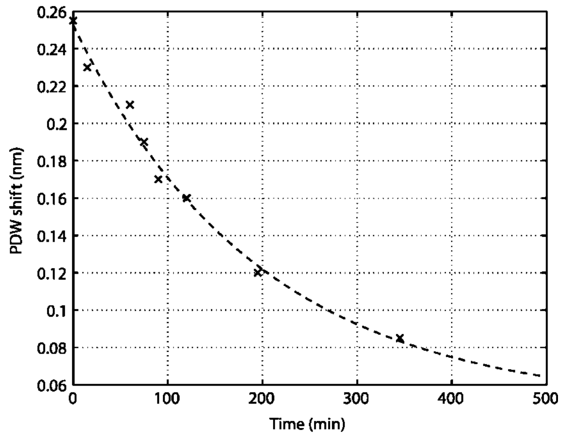


Fig. 6. PDW shift of the add–drop wavelength filter as a function of annealing time. Crosses represent the measured values, and the dashed curve is an exponential fit to the measured values.

ing that this reflection is due to mode conversion between the even and the odd modes. This indicates that the grating is at a slight angle with respect to the waveguide.

Mode intensity profiles of the waveguides for the two mask opening widths, 2 and 5 μm, are presented in Fig. 5. The mode intensity profile for a single-mode fiber is shown for comparison. The waveguide with a mask opening width of 2 μm is a single mode and the waveguide with a mask opening width of 5 μm supports two modes. The waveguide even-mode profiles are almost circular and slightly smaller than the single-mode-fiber mode profile as can be seen from the figure. Also, for the waveguide with a 5 μm mask opening width, the profile of the odd mode is shown.

## 5. Discussion and Conclusions

The results described in Section 4 demonstrate very low birefringence for the UV-written gratings in buried ion-exchanged glass waveguides. This appears to be in disagreement with the performance of our add–drop wavelength filter presented in Ref. 3. Therefore we decided to further investigate the polarization dependence of the add–drop wavelength filter presented in Ref. 3. Note that the device was fabricated in a BGG31 glass substrate using similar waveguide and grating fabrication processes as in this study. First, the PDW shift for the even–odd reflection was confirmed to be ~0.25 nm with the Bragg wavelength of 1564.60 nm for the quasi-TE polarized light. To reduce the birefringence we annealed the sample at 230 °C in successive steps for a rather long total duration of 345 min, and after each annealing step we measured the Bragg wavelength for the quasi-TE and TM modes. The measured PDW shift against the annealing time is shown in Fig. 6. The annealing decreases the PDW shift, but it remains above 0.05 nm, which is not low enough for telecommunication applications. Since these gratings are not much stronger than the ones fabricated in this study, it is unlikely that the measured PDW shift is due to UV-induced birefringence. This conclusion is supported by recent studies on UV-induced birefringence in fiber Bragg gratings.[13,14] We believe that this nonvanishing birefringence is due to the relatively short burial duration of 300 s used in making the add–drop device. As a result, the waveguides locate only slightly beneath the glass surface. The waveguide modes still interact with the surface, which increases the waveguide form birefringence. To confirm this, we used our modeling software for ion-exchanged glass waveguides[15] to determine the form birefringence in a two-mode waveguide fabricated with the parameters in Ref. 3. The calculated values of form birefringence are $5 \times 10^{-4}$ and $2 \times 10^{-4}$, respectively, for the even and the odd modes. After a 345 min annealing at 230 °C, these values decrease to $2 \times 10^{-4}$ and $1 \times 10^{-4}$. These calculated values are in good agreement with the measured PDW shift [see Eq. (2)] after burial. The modeled values after annealing are slightly higher than the measured values. Regarding the Bragg wavelength, it decreased as the sample was annealed due to the decrease of the effective index of the modes [see Eq. (3)]. The Bragg wavelength of 1561.54 nm for quasi-TE polarized light was measured after annealing for 345 min. Interestingly, the reflectivity of the grating dropped only to a value of ~90% from ~99% after this harsh temperature treatment. This implies that these UV-imprinted gratings in BGG31 glass are stable, which is an important requirement for telecommunication devices.

In conclusion, low birefringence, of the order of $2 \times 10^{-5}$ or below for both the even and the odd modes, was observed in UV-written gratings in dual-mode ion-exchanged glass waveguides buried deep enough below the glass surface. The UV-exposed Bragg grating had a small effect on the waveguide birefringence. This result has significance in integrated optical components based on the even–odd mode conversion including add–drop multiplexers,[3] header recognition chips for optical packet switching,[5] and chromatic dispersion compensators.[4] These chip-size integrated optical devices have the potential to replace the spacious fiber-based components utilizing bulky circulators in applications requiring numbers of elements.[2] Another benefit with integrated optical components is easy and accurate manufacturing. Standard photolithographic techniques combined with an UV-grating exposure provide control over the grating reflectivity, element spacing, and location. Therefore utilization of polarization insensitive integrated optical components could greatly reduce the system's size and cost in optical communication networks.

We thank Brian R. West for his help with the birefringence modeling. Support from TRIF (State of Arizona Photonics Initiative) is appreciated. S. Yliniemi also thanks the Academy of Finland and Magnus Ehrnrooth's foundation for financial support. This work was performed while S. Yliniemi was with the College of Optical Sciences at the University of Arizona.

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