FABRICATION AND CHARACTERIZATION OF SILICA-ON-SILICON BASED LONG-PERIOD WAVEGUIDE GRATING

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Abstract: Silica-on-silicon based corrugated long-period waveguide grating is fabricated using standard clean-room processes by making periodic corrugation on top of a relatively high-indexed (contrast ≈ 0.8%) Ge-doped silica waveguide that being sandwiched between un-doped silica under-cladding and boro-phospho-silicate-glass over-cladding layers. Resonance of this 15-mm long waveguide grating is found at ~1581 nm at room temperature, with grating strength of ~11 dB and FWHM bandwidth of 7 nm with negligible birefringence. Temperature characteristic of this waveguide grating is also studied.

1. INTRODUCTION

Long-period fiber grating (LPFG) is well established for last several years for its various applications in the area of optical communications [1] and sensing [2]. In contrast, long-period waveguide grating (LPWG) offers several distinct advantages [3] compared to LPFG due to the flexibility in its structure and material. Recently, LPWGs have been designed [3]-[4], fabricated by use of various techniques [5]-[7] and demonstrated to implement a wide range of applications using a range of polymer materials [5]-[10] by exploiting their large values of thermo-optic coefficient. However, stability and long-term reliability of the device is essential to achieve a commercially viable LPWG.

In this letter, we report our first effort of realizing a silica-on-silicon (SoS) material based LPWG [11] device. Attention is focused on this material not only because of good material stability and technology-maturity, but also for its good compatibility to optical fibers with low insertion loss, and for interaction between the fundamental guided-mode and limited (one or two) cladding-modes with a cross-section of device-dimension that is compatible to a standard single-mode optical fiber.

2. FABRICATION OF LPWG

The proposed LPWG device structure consists of a thick un-doped SiO_2 under-cladding layer with refractive index (RI) of $n_{u\text{-}cl}$ on a silicon substrate, a Ge-doped higher-indexed oxide guiding layer with RI of n_g, thickness d_g and width of w_g, a boro-phospho-silicate glass (BPSG)-based lower-indexed SiO_2 over-cladding layer with RI of $n_{o\text{-}cl}$, thickness $d_{o\text{-}cl}$, where $n_g > n_{o\text{-}cl}$, $n_{u\text{-}cl} > n_{ex}$ ($n_{ex} = 1$, for air). A schematic of the proposed LPWG device is shown in Fig. 1. In this work, thermal-oxided Si-wafer was taken as a starting material and the doped silica layers were deposited by plasma enhanced chemical vapor deposition (PECVD) technique with the help of an equipment supplied by STS, UK.

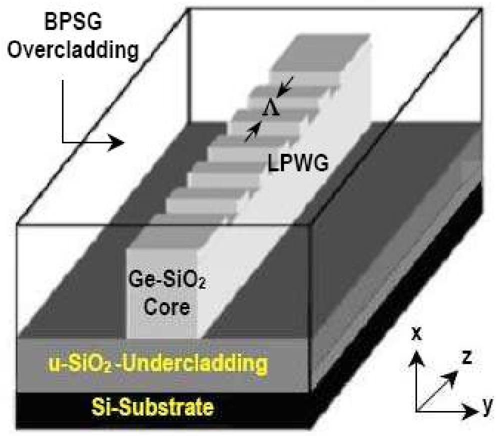

Fig. 1: A schematic of LPWG device based on silica-on-silicon material.

Prior fabrication, the waveguide parameters (e.g., width and height of the channel waveguide for a particular RI contrast between the core and the claddings) and grating parameters (e.g., length, periodicity and the tooth-height of grating corrugation) of the LPWG device were optimally designed so that only fundamental mode can propagate through the core optical waveguide, which can produce a relatively strong rejection band in the wavelength region of around 1.55 μm, after being coupled with any of the co-propagating higher order cladding modes.

The LPWG has been fabricated by use of standard clean-room processes with a proper sequence of various unit-operations, as explained in Fig. 2. Initially, a 4″-diameter SoS wafer with 15 μm thick thermal silica buffer (RI: 1.4448 for transverse electric (TE)-mode and 1.4449 for transverse magnetic (TM)-mode at 1550 nm) was taken, which was supplied by KST, USA. A 6-μm thick Ge-doped silica guiding layer (RI: 1.4570 and 1.4571 for TE- and TM-mode, respectively, at 1550 nm) was deposited on top of it using PECVD, where RI of the guiding layer was maintained by the flow of GeH_4 into the chamber. RI and thickness of deposited wafers were measured by Metricon 2010 prism coupler. Waveguide patterns were made by photo-lithographic technique (Karl Suss, MJB3 mask aligner) after exposing and developing positive photo-resist S1818 (Shipley, USA) spin-coated rectangular pieces of wafer with dimension of ~ 40 mm × 8 mm × 1 mm (length × width × thickness). Device patterns were protected by a thin nichrome layer deposited through e-beam evaporation and then by lift-off processes. Single-mode waveguides of dimension of 6 μm × 6 μm (width × height) was realized by reactive ion etching (RIE) (Anelva, Japan), where SF_6 and O_2 gases were applied at flow-rate of 40 sccm and 4 sccm respectively at a chamber pressure of 75 mTorr with a RF power of ~ 800 W. Actual waveguide thickness was measured by a surface profiler (XP-2, AMBiOS) after removing the nichrome layer. A periodic corrugation on top of one of the two waveguides (other being a reference) was realized after second level of lithography and shallow dry etching. For 15 mm long LPWG, the values of grating-period and tooth-height corrugations were 228 μm and 85 $\pm$ 5 nm, respectively. To observe a strong coupling between core-mode and first cladding-mode in C+L-band, such parameters were considered. A BPSG-based oxide layer of ~ 6 μm thickness (RI: 1.4447 for TE-mode and 1.4453 for TM-mode at 1550 nm) has been deposited on top of the corrugated waveguides in the next stage. This layer works as the over-cladding of the device, where appropriate B- and P-doping levels were chosen by adjusting B_2H_6 and PH_3 flow in the chamber to match its refractive-index to that of thermal oxide under-cladding layer. The sample wafer was then annealed at 1000°C for ~ 4 hours to stabilize this layer with a re-flow on top of both ridge waveguides and to minimize absorption loss [12] of the material.

The device was then diced precisely with a dicing machine (Logitech, UK) according to the exact device-length of 30 mm (15 mm grating with 7.5 mm waveguide without corrugation in its either side). Input/output facets of the device were polished in a polishing machine (Allied TechPrep, Allied High Tech Products Inc., USA). After a preliminary test of the LPWG and reference waveguide (separated by 250 μm) by end-fire coupling, the device was pigtailed with commercial connectorized 2-channel V-grooved fibre array (FA) ribbons (Hataken, Japan) after proper alignment, using a Photonics Packaging Automation System (Newport, USA) by fixing with a UV-curable NOA-61 epoxy, and packaged subsequently in a suitable metallic case for thorough environmental testing. Fig. 3 shows a photograph of the packaged LPWG device. The losses of 30 mm long waveguides, before and after packaging, were measured to be ~3.8 and ~4.4 dB, respectively at 1550 nm. They were almost same for TE- and TM-modes, and also for grating and reference waveguides, which indicates negligible polarization dependent loss, and an extra loss due to shallow corrugation. Using a well-established RIE process and proper facet-polishing further reduce this loss.

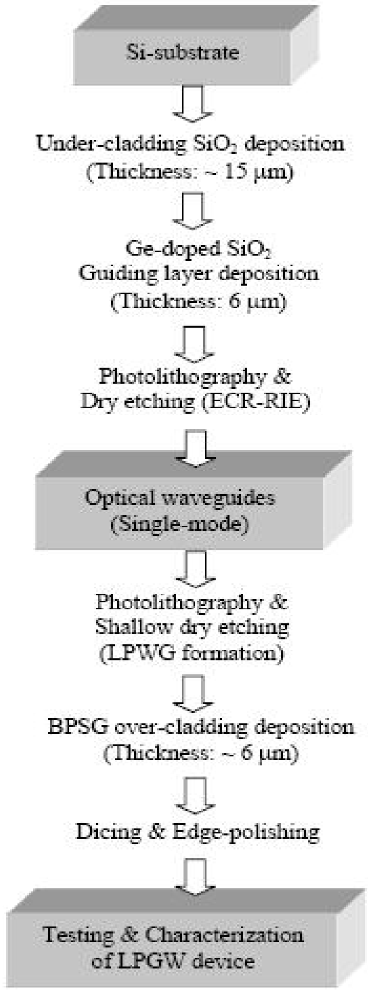

Fig. 2: A sequence of process-steps for the fabrication of SoS LPWG.

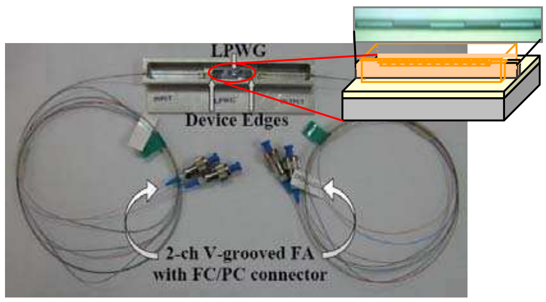

Fig. 3: A photograph of the packaged LPWG.

3. RESULTS AND DISCUSSION

The packaged LPWG was tested over a wider range of temperature to measure the transmitted spectra by placing it inside a control chamber (ESPEC Corp., Japan) and using a broadband ASE light source, a polarization splitter and a HP86140 optical spectrum analyzer. TE/TM-polarized light was coupled to the device through polarization-maintaining fibers. Fig. 4 shows a schematic of the experimental setup for the above measurement.

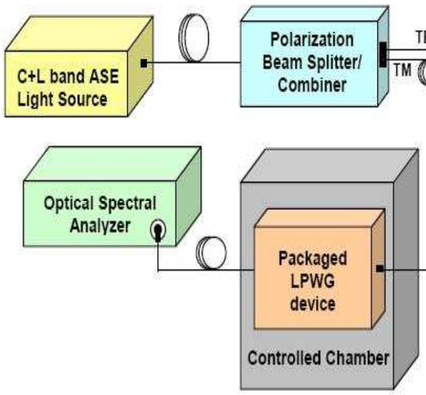

Fig. 4: A schematic of the experimental setup to measure LPWG spectral characteristics at various temperatures.

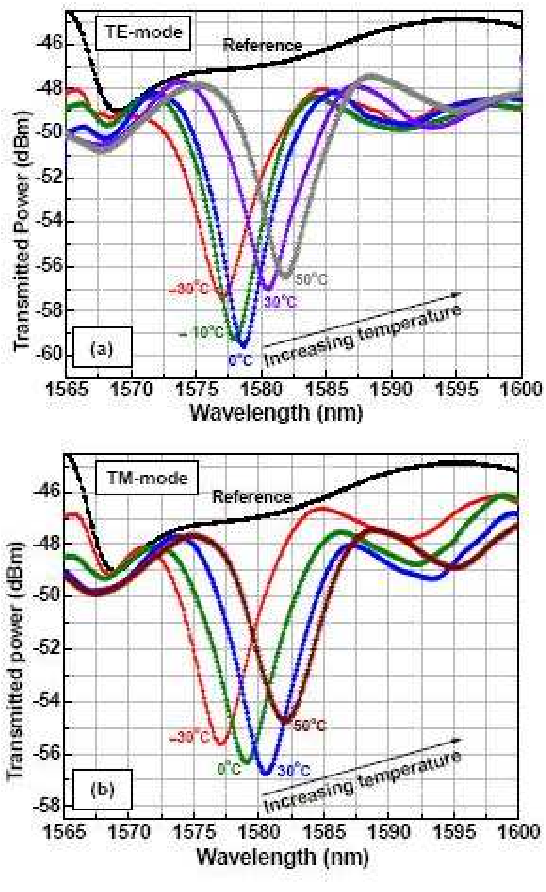

Fig. 5: LPWG transmission spectra measured at different temperature for (a) TE-mode and (b) TM-mode.

Figs. 5(a) and 5(b) display the LPWG transmission spectra for quasi TE- and quasi TM-modes, where LPWG resonance wavelength was observed to vary in 1577 - 1582 nm when temperature varies from –30°C to 50°C. The average contrast of the center wavelength of the rejection band was found to be ~ 11 dB with the average 3-dB bandwidth of ~ 7 nm. Better contrast with minimum side-lobes can be achieved by improving the non-uniformity of grating tooth-height and waveguide-sidewall roughness. Further, the LPWG spectral characteristics were studied with un-polarized light by directly sending the light from the ASE light source to the input of the packaged device, without passing through polarization splitter. The strength of the rejection band was found to be slightly less with relatively larger shift in this temperature-dependent rejection-band in this case compared to those were measured for TE-/TM-mode transmission spectra. The average temperature-sensitivity of the LPWG was estimated to be around 82 pm/°C, 64 pm/°C and 59 pm/°C for un-polarized light, quasi-TE and quasi-TM-mode respectively and those have been plotted in Fig. 6. The above values of temperature-sensitivity were estimated by considering the linear regression among the experimental data within the range of measurement. It is worthwhile to mention at this point that these values are quite similar to the reported values for LPFGs [3]. Very small birefringence was noticed at room temperature, due to symmetric waveguide structure with low RI contrast, resulting in a polarization-insensitive device at that temperature.

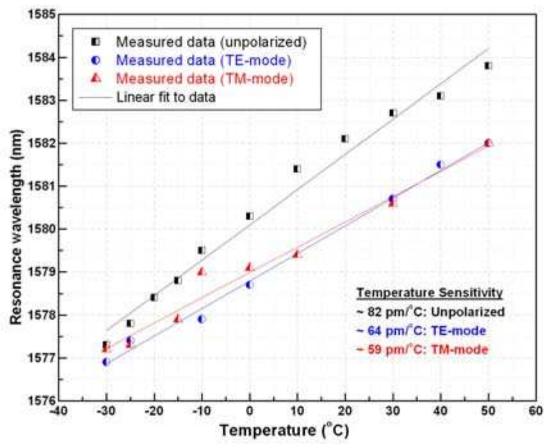

Fig. 6. Shift of center wavelengths for TE-, TM-mode and the un-polarized light with the variation of temperature.

The measured resonance wavelengths (center wavelength of the band-rejection filter in the transmission spectra) for the fabricated LPWG were finally compared with the theoretical phase matching condition of resonance, $\lambda_0 = (N_0 - N_m)\,\Lambda$, where λ_0 is the resonance wavelength, Λ is the grating period, N_0

and N_m are mode indices of the fundamental core-mode and that of the cladding modes, respectively. Simulated resonance wavelength of the LPWG, with the same grating-period of 228 μm, was calculated as 1593.6 nm for TE-mode at room temperature, which is found to be much close to that measured for the fabricated device. The simulation of the phase-matching graphs and the transmission characteristics of the fabricated LPWG (after considering the measured values of the waveguide and grating parameters) for TE- and TM-modes have been displayed in Fig. 7.

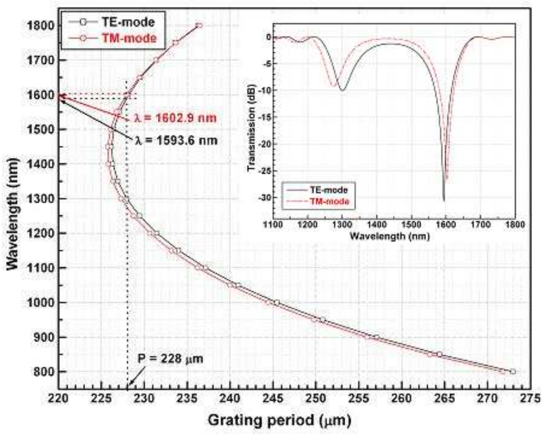

Fig. 7: Simulation of phase-matching graphs and transmission characteristics of the fabricated LPWG.

4. CONCLUSION

Silica-on-silicon based LPWG has been fabricated and demonstrated by making a periodic corrugation (with the periodicity of 228-μm in a grating-length of 15 mm with ~ 85 nm tooth-height of grating corrugation) on top of a Ge-doped silica waveguide that being sandwiched between un-doped silica under-cladding and BPSG over-cladding layers. Resonance wavelength of the grating is found at ~1581 nm having grating strength of ~11 dB with 3-dB bandwidth of ~ 7 nm. Negligible polarization-dependency was observed at room temperature because of symmetric structure with low RI contrast. Temperature response of this LPWG has been found to be similar to that of LPFGs. This device has significant potential for various telecom and sensing applications with better stability and long-term reliability.

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