Realization of Long-Period Corrugated Grating in Silica-on-Silicon-Based Channel Waveguide

Suchandan Pal, Ashok Chauhan, Mahendra Singh, Pawan Kumar, Mukesh Sharma, Nirmal Pradhan, Kuldip Singh, and C. Dhanavantri

***Abstract*—Long-period corrugated grating in silica-on-silicon-based channel waveguide is realized by making periodic corrugation on top of a relatively high-indexed (contrast ≈0.8%) Ge-doped silica waveguide, which is sandwiched between undoped silica undercladding and boro-phospho-silicate-glass overcladding layers. Resonance wavelength of the 15-mm-long grating is found at ~1581 nm, having negligible polarization dependency at room temperature, with a grating strength of ~11 dB and 3-dB bandwidth of 7 nm. The temperature characteristic of the grating is also investigated, which is found to be similar to that of the long-period fiber grating. This device has significant potential for various integrated-optic communication and sensing applications.**

***Index Terms*—Channel waveguide, integrated optics, long-period grating, silica-on-silicon (SoS), waveguide grating.**

I. Introduction

LONG-PERIOD gratings in optical fibers are well established for more than a decade for various important applications in optical communications [1], [2] and sensing [3]. However, long-period fiber gratings (LPFGs) are inappropriate when integration is required; planar integrated optic device is advantageous in this respect. In addition, although long-period waveguide grating (LPWG) is capable of coupling light from fundamental guided mode to selected cladding modes at specific wavelengths [4], [5] by the same principle in which LPFG works, LPWG has other distinct qualities like flexibility in structure and material, ease in mass production, etc.

Recently, LPWGs have been fabricated by use of various techniques [6]–[11], and they have been demonstrated to implement a range of applications including band-rejection filter [6]–[11], bandpass filter [12], variable-tunable filter [9]–[11], and grating coupler [13]. However, most of these LPWGs have been fabricated using a range of polymeric materials [6]–[10], [12], [13] by exploiting their large thermooptic effect in order to realize a wide tunability, where the process of fabrication is also simple. However, to achieve much stable and long-term reliable packaged LPWG device with relatively better compatibility to any standard fiber- or integrated-optic-based measurement system, it is necessary to employ a very stable material and a well-matured technology. In this letter, we report our first effort in the realization of a silica-on-silicon (SoS) material-based LPWG device [14]. Attention is focused on this material not only because of material stability and technology maturity, but also for its good compatibility to optical fibers with low insertion loss, and 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.

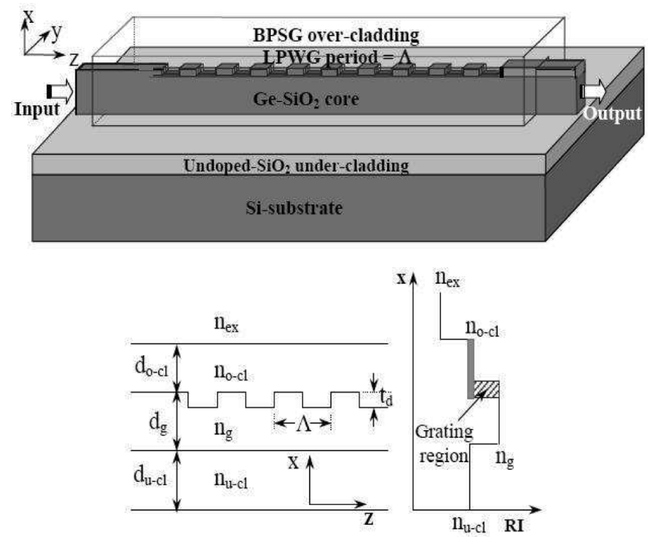

Fig. 1. Schematic of a corrugated LPWG along with its RI profile.

II. Fabrication of LPWG

The proposed LPWG device structure consists of a thick SiO_2 thermal oxide undercladding layer of refractive index (RI) $n_{u\text{-cl}}$ on a silicon substrate, a Ge-doped higher indexed oxide guiding layer of RI n_g, thickness d_g, and width of w_g, a boro-phospho-silicate glass (BPSG)-based lower-indexed SiO_2 over-cladding layer of RI $n_{o\text{-cl}}$, thickness $d_{o\text{-cl}}$, where $n_g > n_{o\text{-cl}}, n_{u\text{-cl}} > n_{\text{ex}}$ ($n_{\text{ex}} = 1$, for air). A schematic of the device and the corresponding RI profile are shown in Fig. 1. In this letter, doped silica layers were deposited by plasma-enhanced chemical vapor deposition (PECVD) equipment (STS, U.K.).

The LPWG has been fabricated using standard clean room processes, as explained in Fig. 2. Initially, a 4-in-diameter SoS

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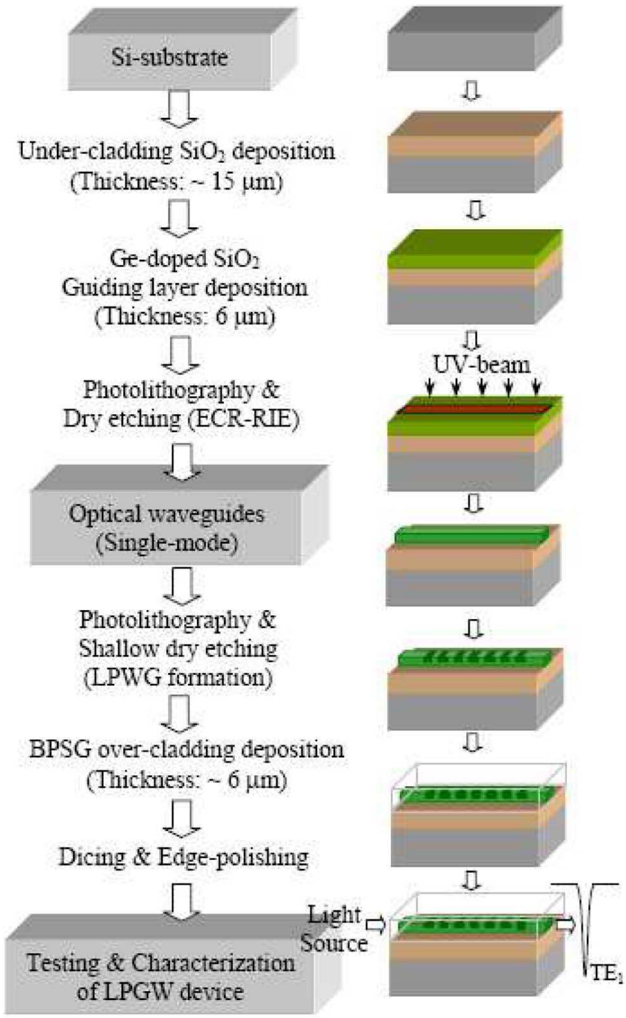

Fig. 2. Sequential process steps for SoS-based LPWG fabrication.

wafer with 15-μm-thick thermal silica buffer (KST, USA; RI: 1.4448 for TE mode and 1.4449 for TM mode at 1550 nm) was taken. 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 the deposited wafers were measured by Metricon 2010 prism coupler. Waveguide patterns were made by photolithographic technique (Karl Suss, MJB3 mask aligner) after exposing and developing positive photoresist S1818 (Shipley, USA) spin-coated rectangular pieces of wafer with dimension of $\sim$ 40 mm $\times$ 8 mm $\times$ 1 mm (length $\times$ width $\times$ thickness). Device patterns were protected by a thin nichrome layer deposited through e-beam evaporation and then by liftoff processes. Single-mode waveguides of dimension of 6 μm$\times$ 6 μm (width $\times$ height) were realized by reactive ion etching (RIE) (Anelva, Japan), where SF_6 and O_2 gases were applied at flow rate of 40 and 4 sccm, respectively, at a chamber pressure of 75 mTorr with an RF power of $\sim$ 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

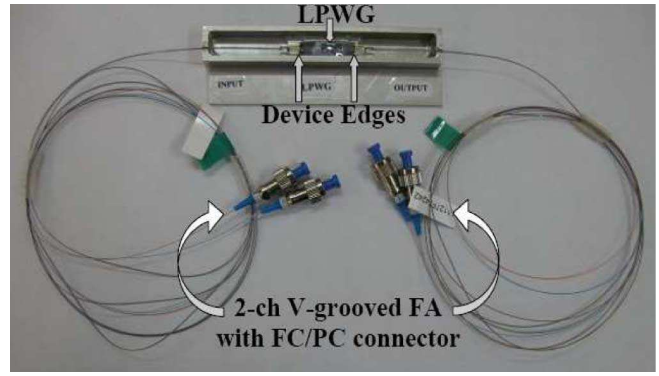

Fig. 3. Photograph of a pigtailed LPWG connected with V-grooved FAs.

a reference) was realized after second level of lithography and shallow dry etching. For a 15-mm-long LPWG, the values of grating period and tooth height corrugations were 228 μm and $85(+/-5)$ 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 overcladding 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 RI to that of thermal oxide undercladding layer. The sample wafer was then annealed at 1000 °C for $\sim$4 h to stabilize this layer with a reflow on top of both ridge waveguides and minimize absorption loss of the material.

The device was then diced precisely with a dicing machine (Logitech, U.K.) 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 two-channel V-grooved fiber 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 $\sim$3.8 and $\sim$4.4 dB, respectively, at 1550 nm. They were almost same for TE and TM modes, and also for grating and reference waveguides, which indicate negligible polarization-dependent loss, and an extra loss due to shallow corrugation. Using a well-established RIE process and proper polishing of facets may further reduce this loss.

III. Experimental Results and Discussion

The transmission spectra of packaged LPWG at various temperatures were measured by placing it inside a control chamber (ESPEC Corporation, Japan) using a broadband amplified spontaneous emission (ASE) light source, a polarization splitter, and an HP86140 optical spectrum analyzer. TE/TM-polarized light

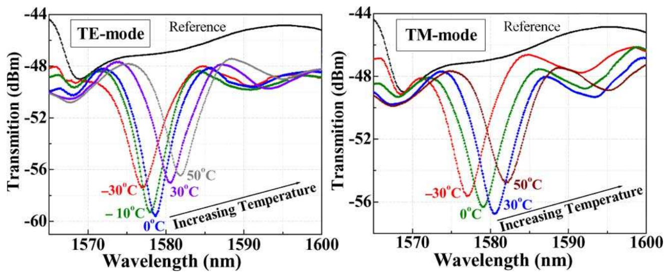

Fig. 4. LPWG transmission spectra for TE and TM modes measured at different temperatures.

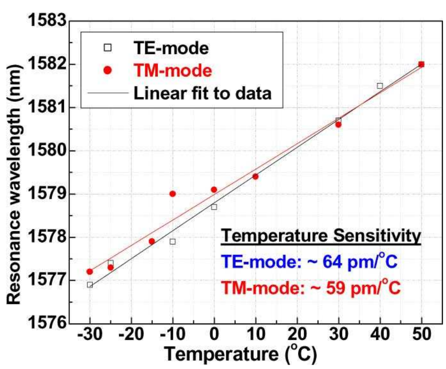

Fig. 5. Shift of TE- and TM-mode center wavelengths with the variation of temperature.

was coupled to the device through polarization-maintaining fibers. Fig. 4 shows LPWG transmission spectra for quasi-TE and quasi-TM modes, where LPWG resonance wavelength was observed to vary in the range 1577–1582 nm when the temperature varies from $-30\,^\circ$C to 50 °C. The best contrast of the center wavelength of the rejection band was found to be 11 dB with a 3-dB bandwidth of 7 nm. Better contrast with minimum side lobes can be achieved by improving the nonuniformity of grating tooth height and waveguide sidewall roughness. Temperature sensitivity of the LPWG was estimated (shown in Fig. 5) to be around 64 and 59 pm/°C for quasi-TE and quasi-TM modes, respectively, which are similar to the reported values for LPFGs [3]. Very small birefringence was noted at room temperature, due to symmetric waveguide structure with low RI contrast, resulting in a polarization-insensitive device at that temperature.

The measured results 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 the mode indexes of the fundamental core mode and that of the cladding modes, respectively. Simulated resonance wavelength of the LPWG, with period of 228 μm, was calculated as 1593 nm for TE-mode at room temperature, which is found to be much close to that measured for the fabricated device.

IV. Conclusion

SoS-based LPWG is realized by making a periodic corrugation (with 228 μm periodicity in a length of 15 nm, having 85 nm tooth height) on top of a Ge-doped silica waveguide, which is sandwiched between undoped silica undercladding and BPSG overcladding layers. Resonance wavelength of the grating is found at $\sim$1581 nm, having a grating strength of $\sim$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 is 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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