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REALIZATION OF CORRUGATED LONG-PERIOD GRATINGS IN SILICA-BASED OPTICAL WAVEGUIDES

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Abstract: Long-period corrugated gratings realized in silica-based optical waveguides have been presented. Following design optimization, waveguide gratings were fabricated through various process steps like PECVD, photolithography, metallization, lift-off, deep/shallow RIE, etc. Waveguide and grating parameters were so chosen that the resonance wavelength of gratings could be achieved at ~ 1.55 μm.

1. INTRODUCTION

Long-period gratings in optical fibres are well-established for more than a decade time for their various important applications in optical communication and sensing. However, these optical fibre-based grating devices are inappropriate when integration is required. Planar integrated optics technology is advantageous in this respect. In addition, these waveguide-based grating structures have other distinct qualities like flexibility in structure and in material, ease in mass production, etc.

Following design optimization, the fabrication and characterization of corrugated long-period waveguide gratings (LPWGs) in silica-based material are presented in this paper. Attention is focused on this material because of its good compatibility to optical fibres with low insertion loss, and for the consideration of interaction among the fundamental core-mode and lower order cladding-modes with a dimension of the structure that is compatible to optical fibre.

2. THEORY

In general, LPWGs can be formed by making partial corrugations on top of a higher-indexed optical waveguide that is sandwiched between lower-indexed under-cladding and over-cladding layers. Based on the coupled-mode theory [1], grating period, Λ, and resonance wavelength of the LPWG, λ_0, are related by a phase matching condition, $\lambda_0 = (N_0 - N_m)\ \Lambda$, where N_0 and N_m (m = 1, 2, 3…) are mode indices of fundamental core-mode and that of the higher order cladding modes, respectively.

3. STRUCTURE OF LPWG DEVICE

The proposed LPWG device structure consists of a thick SiO_2 thermal oxide under-cladding layer of refractive index $n_{u\text{-}cl}$ on a silicon substrate, a Ge-doped higher-indexed oxide guiding layer of refractive index n_g, thickness d_g and width of w_g, a BPSG (Boro-Phospho-Silicate Glass) based lower-indexed SiO_2 over-cladding layer of refractive index $n_{o\text{-}cl}$, thickness $d_{o\text{-}cl}$ and width of $w_{o\text{-}cl}$, where $n_g > n_{o\text{-}cl}$, $n_{u\text{-}cl} > n_{ex}$ (n_{ex}=1, for air). The schematic of device and the corresponding refractive-index (RI) profile are shown in Fig. 1.

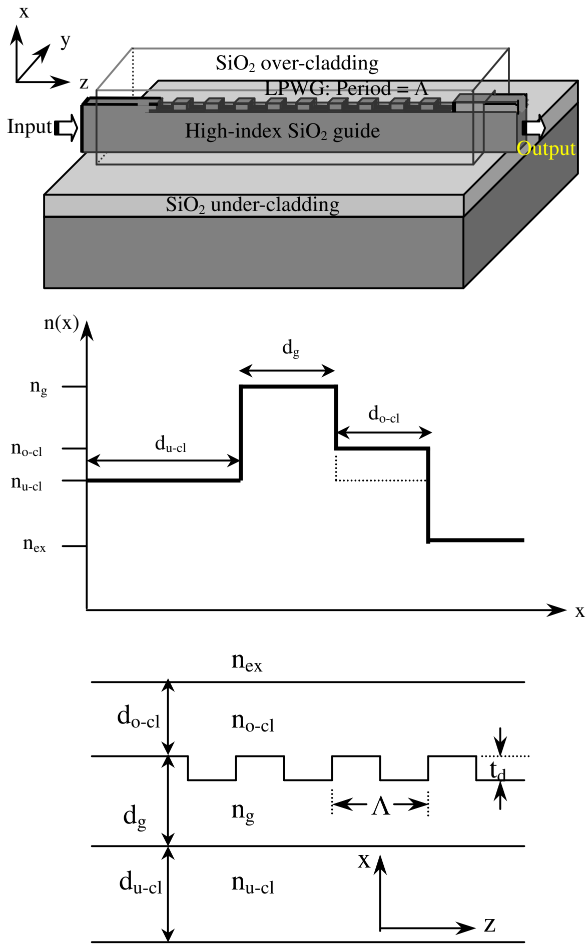


Fig. 1: A schematic of LPWG along with RI profile.

In this work, doped silica layers can be deposited by plasma-enhanced chemical vapour deposition (PECVD) technique, where the silica layers can be produced by using silane (SiH_4) and nitrous oxide (N_2O) as precursors and Ge, B and P impurities are introduced into the layers as dopants using germane (GeH_4), diborane (B_2H_6) and phosphine (PH_3), respectively. The detailed fabrication process steps have been described in the next section. Ge-doping increases the refractive-index in the guiding layer, where the contrast between the guiding and the under-cladding layer can be maintained by the flow of GeH_4. Appropriate B and P-doping levels can be chosen by adjusting B_2H_6 and PH_3 flow in order to match refractive-index to that of the thermal oxide under-cladding layer, and to optimise the reflow properties of the glass over the waveguide.

3. FABRICATION OF LPWGs

Prior to fabricate the device, waveguide and grating parameters were designed [2], [3] optimally after drawing phase-matching curves, so that a relatively strong rejection band can be achieved in the wavelength region of ~ 1.55 μm. Finally, an LPWG has been designed after considering n_g = 1.4570, $n_{o\text{-}cl}$ = 1.4460, $n_{u\text{-}cl}$ = 1.4457, n_{ex} = 1, $w_g = d_g$ = 6 μm, $d_{u\text{-}cl}$ = 15 μm, $d_{o\text{-}cl}$ = 6 μm, $L_{Grating}$ = 15 mm, t_d = 87 nm and Λ = 232 μm. Fig. 2 shows the transmission spectra of the grating simulated by *OptiGrating 4.2*, where the resonance wavelength for TE_1-mode was found to be at 1545 nm having an isolation strength of 43.7 dB with FWHM bandwidth of 15 nm. The other resonance dip at the wavelength of ~ 1312 nm has appeared in the transmission plot due to the dual resonance nature of the proposed LPWG [3].

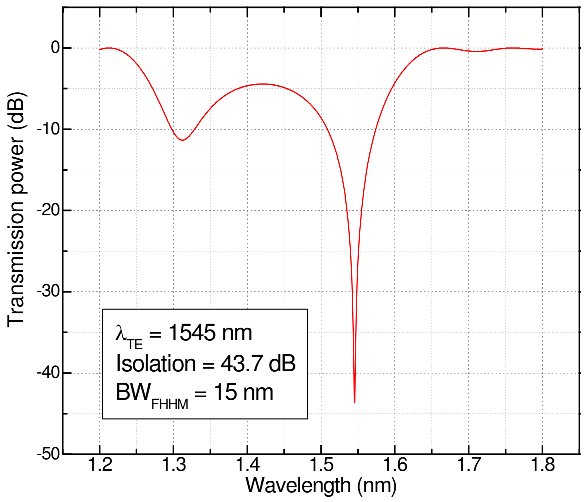
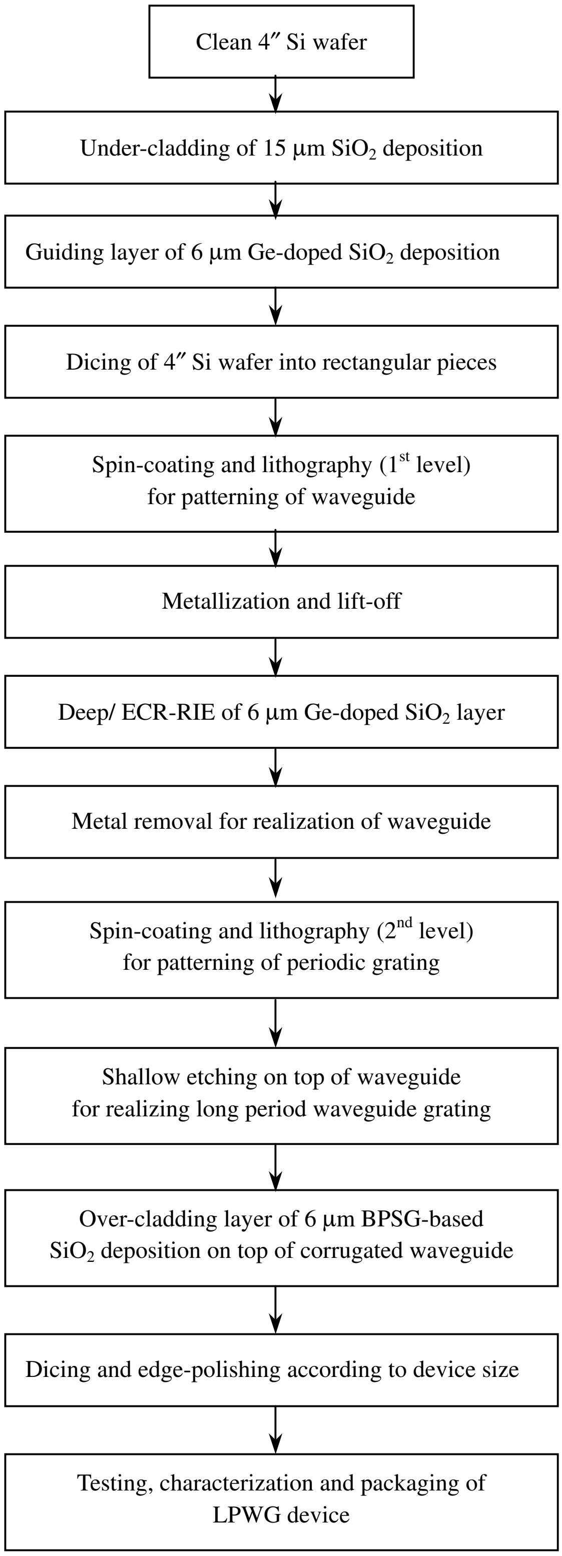


Fig. 2: A typical transmission spectrum of an LPWG simulated in *OptiGrating*.

Following the optimal design of the proposed LPWG device, attention has been focused to fabricate the device based on various design parameters, including waveguide and grating parameters. Various process steps like oxide deposition by PECVD, photo-lithography, deep and shallow dry etching, etc. have been optimized before starting the device fabrication. A detailed flow-chart for the fabrication of the proposed LPWG device is included in Chart 1.

Chart 1



Initially, an un-doped silica layer (refractive index: 1.445) of thickness ~ 15 μm, and on top of it, a Ge-doped silica layer (refractive index: 1.457) of thickness of ~ 6 μm were deposited on a 4″ diameter silicon wafer substrate using plasma enhanced chemical vapour deposition (PECVD) system. Refractive index and thickness of undoped and Ge-doped silica layers were measured by prism coupler (Metricon-2010), where these two layers act as under-cladding and guiding layers, respectively. Waveguide patterns were made by using photo-lithography technique after exposing and developing positive photo-resist spin-coated rectangular pieces of wafer. Device patterns were protected by a thin nichrome layer through metalization and lift-off processes before realizing the optical waveguide by using reactive ion etching (ECR-RIE) technique. Waveguide thickness of ~ 6 µm was measured after removal of the metal layer by surface profiler (XP-2, AMBiOS). Shallow periodic corrugation on top of the optical waveguides was realized after second level of lithography and etching. The values of grating-period and tooth-height corrugations were in a range of 224 – 234 µm and ~ 84 nm, respectively in order to achieve a relatively strong isolation in the rejection band of the waveguide grating in 1.55 µm wavelength region at room temperature. Figs. 3(a) and 3(b) show the photograph of the LPWGs along with the reference waveguide and the corresponding step-height measurement of the device after a periodic shallow dry etching on top of the waveguides in order to realize the LPWGs.

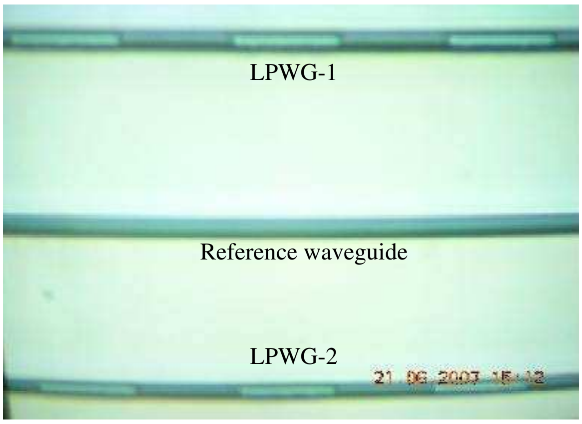


Fig. 3(a): Photograph of LPWGs along with reference waveguide, after 2nd level lithography.

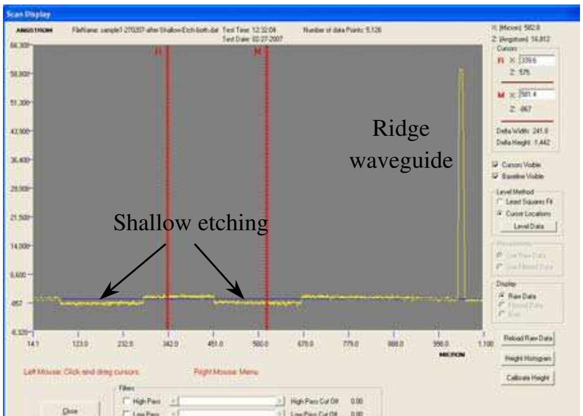


Fig. 3(b): Step-height measured by XP-2, AMBiOS, after shallow etching on top of waveguide to realize LPWGs.

The BPSG-based oxide layer of around 6 µm thickness having a relatively lower refractive-index has been deposited on top of the corrugated waveguides in the next stage. This layer works as the over-cladding layer of the device. The device sample was then annealed properly at 1000°C for around 4 hours in order to achieve a stabilized oxide layer with a re-flow on top of the device. The periodic corrugations of the LPWGs are then almost indistinguishable, as shown in Fig. 4, as the contrast between the refractive-index (RI) layers (waveguide-layer and the over-cladding layer) are very less (RI contrast of the order of 0.01) and at the same time, the tooth-height corrugation of the gratings are also very low (~ 84 nm).

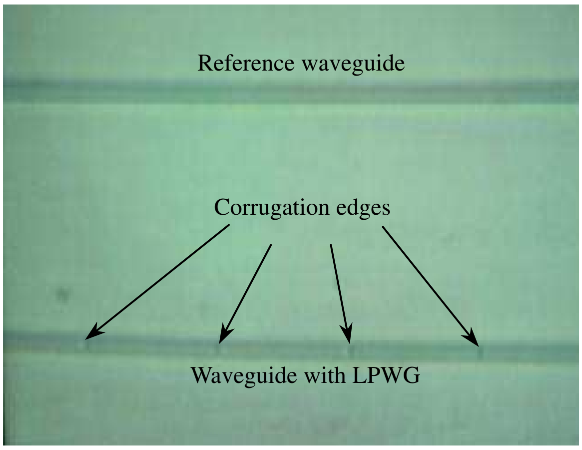


Fig. 4: Photograph of LPWG along with reference waveguide after deposition of BPSG over-cladding.

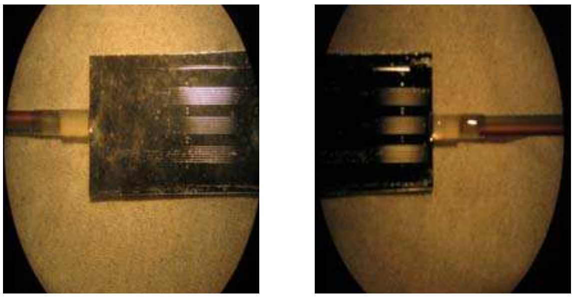


Fig. 5(a): Pig-tailed LPWG device (input and output sides) with v-grooved fibre-array ribbon.

Fig. 5(b): Packaged LPWG device with 8-channel v-grooved fibre-array ribbon.

The processed wafer-piece was then diced according to the size of the device by a DISCO dicing machine and subsequently both the input and output edges were polished before testing and characterization of the device. After a preliminary testing of light propagation through the waveguides (LPWG and reference waveguide), the device was pigtailed with 8-channel v-grooved fibre array (FA) ribbon both in input and output sides and packaged in a suitable metallic case. Figs. 5(a) and 5(b) show the photographs of the pigtailed LPWG device and the same device after appropriate packaging, respectively.

4. RESULTS AND DISCUSSION

The fabricated LPWG device consists of eight individual straight waveguides, including one reference waveguide with a separation of 250 μm (center-to-centre) among each waveguide. A 8-channel FA ribbon was used both at the input and output sides for pig-tailing purpose. Total device length was measured to be ~ 30 mm, out of which the length of the in-built corrugated grating was 15 mm within the waveguide. Average insertion loss of 4.4 dB was measured (including input and output coupling-loss between the source-to-device and the device-to-detector coupling points) in each individual channel by light propagation over the waveguide length of ~ 30 mm.

More detailed results related to the spectral characteristics of this silica-based LPWGs and their variation with respect to the changes in the grating parameters along with the applied temperature would be presented.

5. CONCLUSION

Corrugated long-period gratings realized in silica-based optical waveguides have been presented in this paper. Following the optimization in design, waveguide gratings were fabricated through various process steps like PECVD, photolithography, metallization, lift-off, deep/shallow RIE, etc. after the optimization in all the above processes. Waveguide and grating parameters were so chosen in this scheme that the resonance wavelength of gratings could be achieved at ~ 1.55 μm. The precision in the values of refractive-indices and thickness of the layers, grating-period and the tooth-height of grating corrugations are found be of vital importance in order to achieve an expected result for the LPWG device.

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