

Double component long period waveguide grating filter in sol-gel material

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Abstract: An efficient, tunable Long Period Waveguide Grating (LPWG) filter based on a new hybrid sol-gel material is demonstrated. The LPWG exhibits an attenuation of -22 dB and a high temperature sensitivity of ~ 3.3 nm/°C. At room temperature the device shows an almost polarization independent wavelength. We took the advantage of the UV-curable sol-gel materials and used soft lithography to demonstrate a simple approach of integrating two LPWG filters on the same structure. The gratings were fabricated on the top and on the bottom of the same ridge waveguide and operate at communication wavelengths of 1550 and 1310 nm, respectively.

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References and links

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1. Introduction

Organic-inorganic optical materials have been the subject of significant recent technological advances with the aim of commercial deployment, especially for telecommunication applications. Sol-gel materials for integrated optical circuits exhibit several advantageous features. The raw materials are lower cost than their crystalline and semiconductor counterparts and offer more flexible fabrication methods [1]. Sol-gel materials can be spin-coated on glass, silica, and silicon, and therefore are compatible with most optical materials. A distinct feature of sol-gel, compared with other optical materials, is the strong temperature dependence of its refractive index [2]. The large thermo-optic coefficient of sol-gel materials can be leveraged to produce efficient thermo-optically tunable components. The use of UV-curable sol-gel materials enable optical features such as microlenses and waveguides to be fabricated [3,4]. One of the key components in optical communication is the long-period grating (LPG). LPG is easy to fabricate and has many applications, such as band-rejection filters [5], gain flattening elements [6], optical sensors [7], and wavelength selective polarizing elements [8]. Most of these devices are fabricated in optical fibers. Although they have various advantages as mentioned above, they also have some limitations. First, there are few degrees of freedom in the design of a long-period fiber grating since it is based on a ready-made optical fiber. For example, the number of exploitable modes or their dispersion characteristics is given. Second, since the fiber is made of silica, the thermo-optic tuning of LPG is inefficient. To circumvent the geometry and material constraints of an optical fiber, LPGs have been implemented in planar optical waveguides [9, 10, 11]. Up to now, most LPWGs have been realized in polymer materials, while LPWG devices based on sol-gel materials remains relatively unexplored. A large number of devices based on sol-gel materials have been demonstrated such as diffraction grating [12], planar waveguides [4], optical chemical sensors [13], and lasers with dynamic distributed feedback [14], but no work has been reported on the fabrication and characterization of LPWG based on sol-gel materials. The fabrication of LPWGs has been mostly limited to standard semiconductor fabrication techniques such as reactive ion etching. An alternative fabrication technique that takes advantage of the UV-curable sol-gel material is soft-stamp replica-molding lithography [15].

In this letter, we report what is believed to be the first example of structural long-period waveguide gratings based on hybrid sol-gel material. The gratings were fabricated by soft lithography using the replica molding and stamping technique. Polarization dependence of the wavelength and the temperature sensitivity of the LPWG were investigated, because temperature sensing is one of the possible applications. The fabricated LPWG filter can be tuned linearly over a large band with a temperature control less than 10 °C. We proposed and demonstrated two LPWG structures, the standard structure where the gratings are fabricated on the top of the ridge waveguide (structure-I) and a new structure with gratings integrated on

the top and on the bottom of the same sol-gel ridge waveguide (structure-II). The devices were operated at communication wavelengths of 1550 and 1310 nm, respectively. The integration of two filters on the same structure can drastically reduce the size and cost of the device.

2. Fabrication

The hybrid sol-gel material used in this study is a fluorinated methacrylic characterized by the presence of fluorine functionality, a methacrylic polymerizable group and diphenylsilanediol (DPSD) composed of silanol groups. The methacrylic end-group is considered suitable for cross-linking during the UV curing step, while the fluorinated group is ideal for refractive index control. As the fluorinated silane contents are varied, the structural evolution and refractive index of the synthesized resin are then controlled. More details regarding material synthesis can be found in a previous publication [4].

The first step in the replica molding process is the production of a mechanically flexible polydimethylsiloxane (PDMS) stamp. The master was fabricated using conventional process for polymer waveguide devices. Spin-coating and thermal curing is used to form polymer thin films (AZ9260). Thermal evaporation of gold, photolithography, sputter-etching of gold, and reactive ion etching (RIE) in oxygen are used to form the channel waveguide with a corrugated structure and prescribed pitch. The PDMS liquid is poured atop the master structure and cured for 3 h at 50 °C. The cured PDMS stamp is peeled from the master device and diced to the required size. Before making the device with the gratings on both sides of the waveguide, LPWGs were fabricated separately with the grating on the top of the waveguide operating in the 1550 and 1310 nm telecommunication window. Figure 1 shows the fabricated devices and Fig. 2 shows the fabrication process of structure-II.

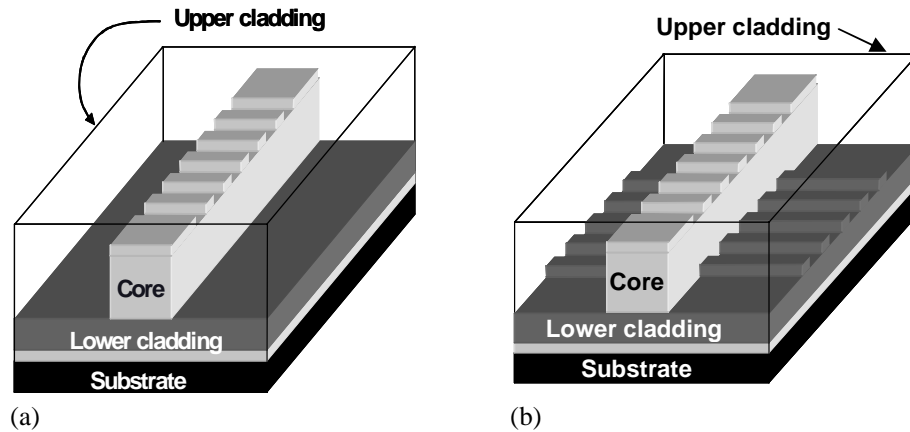


Fig. 1. Two possible configurations for physically patterned LPWG in optical waveguides: (a) Grating patterned on the top of the core, (b) Grating patterned both in top and bottom of the core.

To fabricate the lower cladding the fluorinated methacrylic was spin-coated on silicon substrates, which had a 2 μm grown SiO_2 layer on the surface. The film was cured by UV-light in a nitrogen atmosphere. The bottom grating with a period of 222 μm was stamped on the lower cladding and UV cured before removal of the PDMS mold. By using the same technique, the core with grating period of 356 μm on the top side was stamped on the bottom grating and UV cured. The depth and length of the gratings are ~ 500 nm and 17 mm, respectively, while the width and thickness of the cross section of the molded waveguide core are 6 and 5.8 μm , respectively. The refractive index of the core material is 1.506; the

refractive index and thickness of the lower cladding are 1.5 and 10 μm , respectively. All refractive indexes are for TE-mode and were measured by prism coupling method (Metricon PC-2010 Prism Coupler). Due to the process of molding with a soft stamp, a thin background residue of the core material is present. Finally, another 11 μm thick film (same material as the lower cladding) was spun on as the upper cladding and UV cured in a nitrogen atmosphere. The final structure was baked at 170 $^{\circ}\text{C}$ for 3 hours. The center wavelength and attenuation of each resonance band are determined by different parameters including the upper cladding thickness. The variation of the cladding thickness can make the core mode to couple to different cladding modes [16]. The 11 μm thick upper cladding is chosen such that the core mode is coupled to the first cladding mode. In order to keep the fabrication process simple and reduce the fabrication time, we chose the same cross section of the waveguide and the same grating depths for both structures. Therefore, during the photolithography and reactive ion etching processes (fabrication of the master), both structures can be fabricated at the same time. The cross section of the structure patterned by replica molding is shown schematically in Fig. 3.

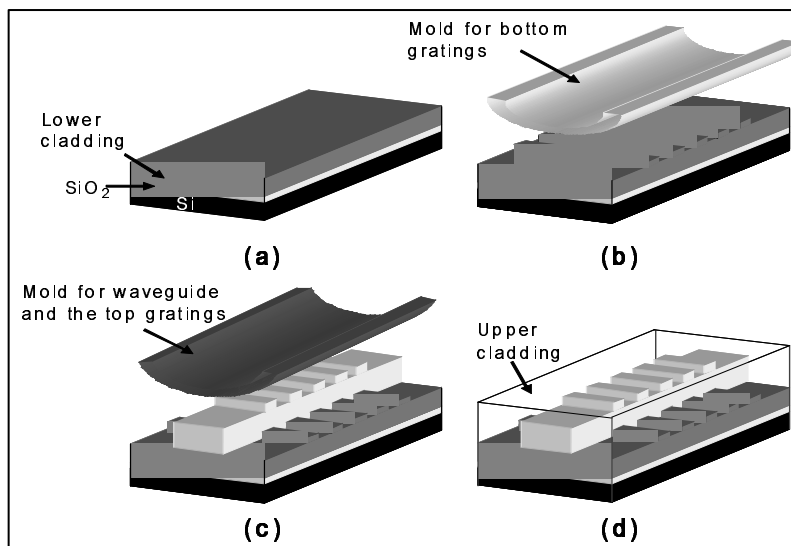


Fig. 2. Fabrication process of the waveguide with two different periods of grating: (a) Lower cladding coating, (b) Stamping the bottom gratings, (c) Stamping the ridge waveguide with grating on the top side, (d) Upper cladding coating. (Figure not drawn to scale).

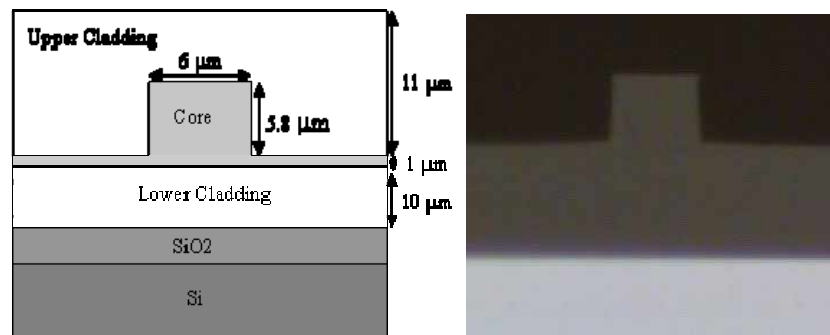


Fig. 3. Cross-section of sol-gel channel waveguide and microscopic image of fabricated waveguide: (a) cross section, (b) optical image.

3. Experimental results and discussion

To prepare for measurement, the substrate is cleaved and the waveguide end-facets are left unpolished. Light from a broadband source in the 1550 nm window or a broadband super luminescent light-emitting diode operating around 1300 nm is fed through a polarizer and input into the LPWG. The output signal is collected using single mode fiber and is measured using an optical spectrum analyzer (OSA). The end-facets of the waveguide are similar and they can serve as both an input and output waveguide.

Figure 4 shows the normalized transmission spectra of structure-I for transverse electric (TE) and transverse magnetic (TM) polarizations measured when no heat was applied to the device. As shown in Fig. 4(a), a transmission peak of ~ -22 dB at a resonance wavelength of 1541 nm was observed with a grating period of $356 \mu\text{m}$. The wavelength difference between TE and TM modes is 0.56 nm. In Fig. 4(b), a transmission peak of ~ -22 dB at a wavelength of 1303 nm was obtained with a grating period of $222 \mu\text{m}$. The wavelength difference between TE and TM polarizations is 0.45 nm. As can be seen from Fig. 4, at room temperature the devices show an almost polarization independent wavelength. The results are in good agreement with our previous work that the material has very low birefringence [2]. The sidebands in the transmission spectrum may arise from the coupling of the core mode to other cladding modes.

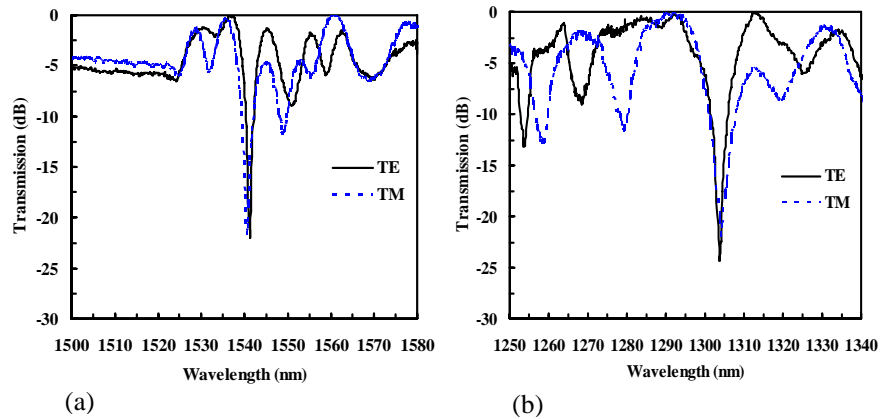


Fig. 4. Normalized transmission spectra for TE and TM polarizations measured when no heat was applied to the substrate: (a) 1550 nm window, (b) 1310 nm window.

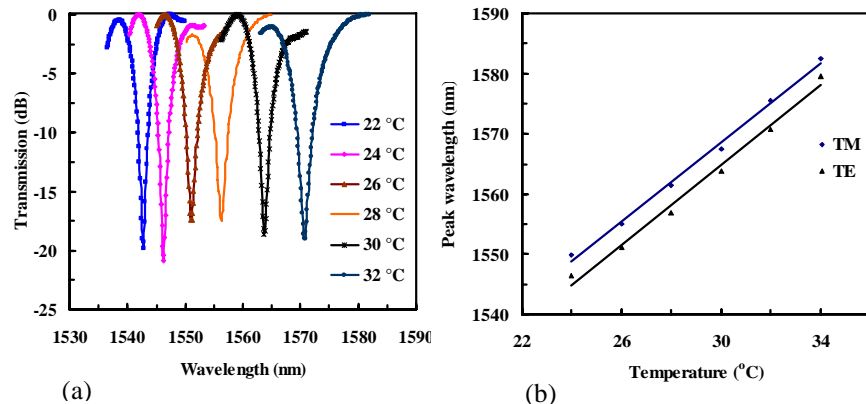


Fig. 5. (a) Normalized transmission spectra of LPWG for TE polarization measured at different temperatures, (b) dependence of LPWG transmission peak wavelength on temperature.

The transmission spectra of the structure-I were measured for both TE and TM polarizations at different temperatures. Figure 5(a) shows the results for the TE polarization at a wavelength of 1550 nm. The center wavelength shifts to longer wavelengths as the temperature increases. The reason for this is that the applied temperature increased the average temperature of the guide and cladding. The net was a reduction of the mode index due to the negative thermo-optic coefficient of the material, and hence, a shift in the resonance wavelength to the longer wavelength according to the phase-matching condition [6]. The peak wavelength of the LPWG filter can be controlled by the thermo-optic (TO) effect. The results for the TM polarization are similar except that the resonance wavelength was extended 4 nm more than that of the TE polarization, when measured at the same temperature (a temperature higher than the room temperature). The TE/TM spectral shift is due to the stress induced when the temperature is applied. The resonance wavelength of both polarizations exhibited the same temperature sensitivities (3.3 nm/°C), as shown in Fig. 5(b). The resonance wavelength is shifted by 33 nm with a temperature change of 10 °C. With this sensitivity, the center wavelength can be tuned over the C band with a temperature control less than 15 °C. Both the wavelength-tuning range and the temperature sensitivity of this filter show better than or comparable results to that achieved with other LPGs. Table 1 shows a comparison between sol-gel LPWGs, polymer LPWGs and fiber LPGs.

Table 1. Comparison between thermal and optical responses of different long period grating

Long Period Grating	$d\lambda/dT$ (nm/°C)	Wavelength Shift $\Delta\lambda$ (nm)	Temperature ΔT (°C)	Transmission Peak (dB) at 1550 nm Wavelength
Sol-gel-LPWG (this work)	3.3	33	10	-22
Polymer-LPWG [9]	-0.165	9	55	-13
Polymer-LPWG [17]	0.89	10.4	12	-13
Polymer-LPWG [18]	15	90	8	-25
Tunable filter [19]	0.8	50	60	-6
Fiber grating [20]	15.8	105	6	-32.2

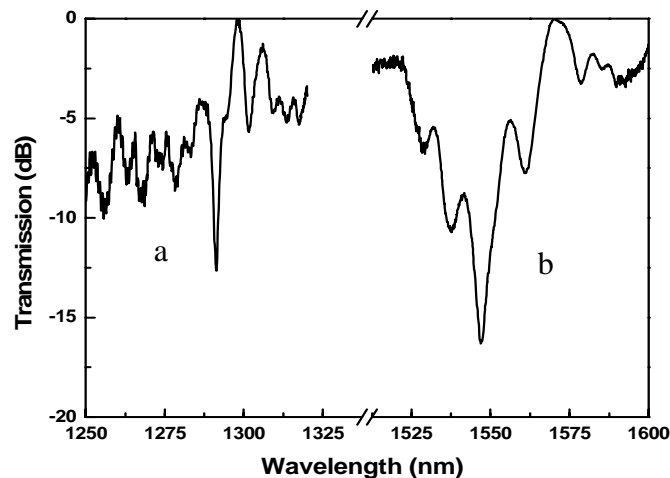


Fig. 6. Normalized transmission spectra of structure-II for TE polarization: (a) 1550 nm window, (b) 1310 nm window.

The fabrication of a corrugated structure in the sidewall of the ridge waveguide has been reported [21, 22]. However, the fabrication process is more complicated and time consuming. We took the advantage of UV-curable sol-gel materials and used soft lithography to fabricate a corrugated structure in the sides of the same ridge waveguide (structure-II, Fig. 2). Figure 6 shows the normalized transmission spectra of structure-II for TE polarization. As shown in Fig. 6(a), a transmission peak of ~ -16 dB at a resonance wavelength of 1547 nm was observed with the grating on the top side of the waveguide. In Fig. 6(b), a transmission peak of ~ -12 dB at 1291 nm was obtained with the grating on the bottom side of the waveguide. In the case of structure-I, the grating pitch was designed to couple the fundamental core mode to the first cladding mode. We used the commercial full-vector mode solver FIMMWAVE (Photon Design) to design the structure-I. Because of the mode solver can not handle the design of structure-II, the gratings of structure-II were fabricated by the same mold (master) used to make structure-I. Therefore, it is difficult to label the cladding modes of structure-II according to their electric-field patterns. The transmission spectra of structure-II presented an oscillating behavior that limits the transmission by several dB. The behavior is typical of lossy grating due to the coupling of the guided mode with other cladding modes.

There are two potential reasons for the degradation of the optical response of structure-II: the variation of the ridge's thickness between the two sets of gratings and the background residue. In the case of structure-II, the channel waveguide "see" a perturbation of 500 nm on both sides of the core. This perturbation of ± 1 μm will increase the scattering loss and contributes to the distortion of the transmission spectrum. Several effects of the background residue were investigated numerically, including the modal properties of an individual waveguide, the coupling ratio of a directional coupler, and the radiation loss in a waveguide bend [23]. In that work, the authors demonstrated that the effective index of the structure increases as the background residue increases in thickness, hence the background residue in structure-II could be the main reason for the degradation of the spectral shape of the transmission and the wavelength shift observed between the two structures. It is possible to improve the optical response of a double sided grating structure by optimizing the design and fabrication process, these will be the subject of a future study.

4. Conclusion

An efficient tunable LPWG based on UV-sensitive sol-gel material is fabricated by a replica molding and stamping technique. The transmission spectrum is thermally tuned using the thermo-optic effect. Peak wavelength is shifted over 30 nm in the temperature range of 24-34 $^{\circ}\text{C}$ and the thermal tuning efficiency is 3 nm/ $^{\circ}\text{C}$. At room temperature, the device shows an almost polarization independent wavelength. We took the advantage of the UV-curable sol-gel material and successfully demonstrated a simple fabrication process to integrate two LPWG filters on the same structure and operating at communication wavelengths. The integration of two filters on the same structure could drastically reduce the size and the cost of the device.

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