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Single Resonant and Widely Tunable Ultrathin Cladding Long-Period Fiber Grating Filters

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A spectrally single resonant and widely tunable, ultrathin cladding long-period fiber grating (UCLPG) is demonstrated in the present paper. Both experimental and theoretical analyses of the characteristics for the proposed device are accomplished. Since the single resonant and widely tunable characteristics of the proposed UCLPG are strongly influenced by the waveguide structure and surrounding material, both material dispersion and waveguide dispersion were included in the calculation for determining the wideband tuning range and resonant spectra of the UCLPG. The tuning range covered wavelength from 1.41 to 1.56 μm for the variation of refractive index of 1–1.445 (optical liquid $n_D = 1.456$ for $\lambda = 1.5$ μm) is achieved in the study.

Keywords: ultrathin cladding long-period fiber grating (UCLPG), dispersion, sensor

1. Introduction

Long-period fiber gratings (LPGs), based on coupling with a guided core mode in co-propagating modes in an optical fiber, have been widely used as band-rejection filters, wavelength dependent loss filters, mode converters, and high sensitivity sensors.[1)] Recently, due to the rapid development of ultra-wide band (S^+–L band) gain amplifiers, a broadband gain flattening device is needed. The LPG appears to be a good candidate for gain flattening applications.[2)] However, a typical LPG filter for gain flattening or wideband applications seems to be not practical nor useful because of loss due to the multiple cladding modes and narrow bandwidth of resonant peaks. To overcome this shortcoming, Oh *et al.* theoretically presented a new LPG filter that significantly enhances the free spectral range (FSR) by controlling the waveguide dispersion of the cladding modes in fluorine-doped-cladding LPG.[3)] Their model further enabled to control material dispersion in the cladding region using doped ions Cr^{3+} to change the effective indices for the cladding modes,[4)] thereby changing the phase-matching conditions of LPGs as well. However, the proposed methods are not very effective due to difficult fabrications of such special fibers. Another technique to enhance the FSR of LPG involves etching the fiber cladding with hydrofluoric acid (HF). The device proposed by Yin *et al.* is based on a HF-etched ultrathin LPG which is surrounded by a dye-doped nematic liquid crystal (NLC) for tuning the resonant wavelengths.[5)] The NLC in the outer cladding of the proposed LPG is tuned by photochemically driving the molecular reorientation by using a polarized Ar^+ laser. Such a device structure complicates the fabrication. Furthermore, based on the experimental results, the tuning range of the resonance peak of LPG is not wide enough for wideband applications because of the limitation of the power of the Ar^+ laser causing the variation of refractive index of NLC. Again, Yin *et al.* theoretically analyzed a HF-etched ultrathin LPG for sensing application with high order cladding mode coupling to provide a single resonant peak over a wide wavelength range of 120 nm.[6)] Chiang *et al.* also demonstrated a widely tunable band-rejection filter using a metal long-period grating deposited directly on the cladding of a polymer waveguide with the center wavelength tuned over the C–L band (1550–1590 nm).[7)]

In this paper, we will present experimental characterization and theoretical simulation results on the study of a HF-etched and UV-written LPG with silica for the first cladding layer and an optical Cargille liquid as the second layer of the cladding for making LPG single resonant over a very broad tuning range. The effective index of the cladding modes will be greatly changed when the proposed ultrathin cladding long-period fiber grating (UCLPG) are immersed in different optical Cargille liquids at different ambient temperatures. The tuning range can cover the wavelength 1.41–1.56 μm (150 nm) for the variation of the refractive index of 1–1.445 (optical liquid $n_D = 1.456$ for $\lambda = 1.5$ μm). To the best of our knowledge, this is the widest tuning range in reported LPG-based devices.[5–7)] Both experimental and theoretical analyses of the practical LPGs are accomplished. In numerical simulation, both the waveguide dispersion and the material dispersion should be considered. The simulated and experimental results are presented, which show a very wide tunability with single resonant transmission spectra for the proposed UCLPGs.

2. Simulation and Experiment

In this section, theoretical analysis and experimental process are described. In numerical calculation, the spectral characteristics of UCLPGs can be readily solved by the coupled mode equations[8)] if the effective indices of guided core mode and cladding modes are known. The single resonance peak of the designed UCLPG is extended over an extremely wide wavelength range. Therefore, the material dispersion should be considered in the simulation processes.

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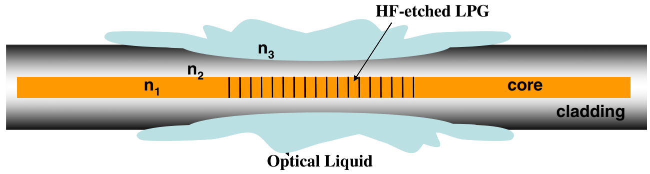

Fig. 1. (Color online) The diagram of the HF-etched ultrathin-clad LPG (UCLPG).

The dispersive characteristics of pure silica: SiO_2 and silica doped with dopants such as GeO_2 have been precisely calculated by using the Sellmeier equation, eq. (1) if the Sellmeier coefficients of the material are known:[9)]

$$n^2 - 1 = \sum_{i=1}^{3} \frac{A_i \lambda^2}{\lambda^2 - B_i^2}, \tag{1}$$

where A_i and B_i are Sellmeier coefficients, λ is wavelength in the unit of μm, the silica doped with GeO_2 used in this designed case are: $A_1 = 0.6961663$, $B_1 = 0.0684043$, $A_2 = 0.4079426$, $B_2 = 0.1162414$, $A_3 = 0.8974994$, $B_3 = 9.896161$ for pure silica (cladding), and $A_1 = 0.7003729$, $B_1 = 0.0684259$, $A_2 = 0.41973080$, $B_2 = 0.11767400$, $A_3 = 0.89583358$, $B_3 = 9.97010026$ for about 3.8 mole% GeO_2 doped (core) in photosensitive single mode fiber on estimation. Then, the effective indices of core mode and multiple cladding modes can be determined by solving the dispersion relations of three layer optical fiber.[6)] Once the effective indices of the core and cladding modes of the fiber are calculated, the resonant wavelengths for the phase-matched condition of UCLPGs can be expressed as:

$$\lambda_p^m = (n_{\text{eff-co}} - n_{\text{eff-cl}}^m) \cdot \Lambda, \tag{2}$$

where the $n_{\text{eff-co}}$ and $n_{\text{eff-cl}}^m$ are the effective indices of core and the m-order cladding modes, Λ is the grating period of LPG.

In experiment, the original LPG was fabricated by UV laser writting technology on a high pressure-H_2-loaded commercial photosensitive fiber with the grating period of about 280 μm and grating length of 2 cm. Then, the LPG was etched by HF until the diameter of cladding is decreased down to 30 μm. After that, the device was immersed in the Cargille liquids in an acrylic thin grooved subtract which is attached on a thermoelectric (TE) cooler for temperature control. The diagram of the device is shown in Fig. 1, where n_1, n_2, and n_3 are the refractive index of the core, cladding and optical liquid, respectively. In measurement, the transmission spectra of the proposed devices are measured by the optical spectrum analyzer (OSA) with utilization of a wide band light source (WBLS) with wavelength range 1.25–1.65 μm (spectral power density > −26 dBm/nm).

3. Results and Discussion

In the following simulation, core and cladding diameter of the fiber device are set to be D_{co} and D_{cl}, respectively. The effective index of the cladding modes in the LPG can be determined by the dispersion relations of the three layer optical fiber.[6)] Figure 2(a) shows the calculated effective indices of the first five cladding modes of the LPG with $D_{cl} = 60$ μm and $D_{co} = 8.3$ μm, and (b) phase-matching grating periods vs the coupling wavelengths corresponding the first five cladding modes when the ambient material as the second layer of the cladding is air. One can see that there are multiple resonant peaks when a certain grating period is written on the fiber.

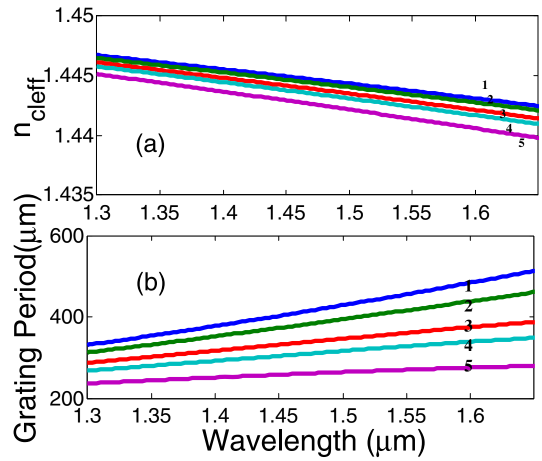

Fig. 2. (Color online) (a) Calculated effective indices of the first five cladding modes of the LPG with $D_{cl} = 60$ μm, and ambient material of air, (b) the phase-matching grating periods versus the coupling wavelengths for the first five cladding modes.

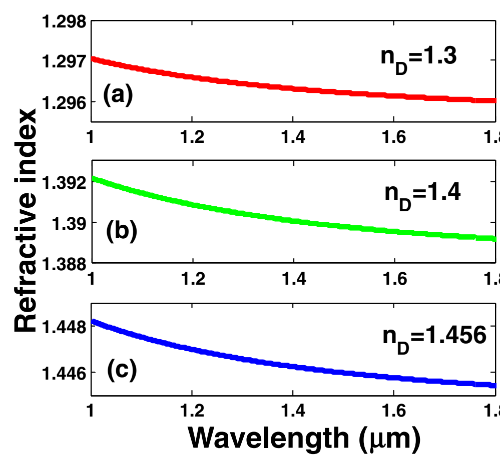

Fig. 3. (Color online) The material dispersive characteristics of the Cargille optical liquids for (a) $n_D = 1.3$, (b) $n_D = 1.4$, and (c) $n_D = 1.456$ at 25 °C.

Figure 3 shows the refractive indices versus wavelength of commercial Cargille optical liquids used in our experiments for 25 °C. In the figure, the label n_D means the measured refractive index of the liquid at the wavelength of 589.3 nm at 25 °C. The optical properties of the liquids are characterized by the thermo-optic coefficient $dn_D/dT = -3.74 \times 10^{-4}$/°C, and the optical transmittance 88% at 1300 nm and 80% at 1550 nm for 1-cm-long interaction length.

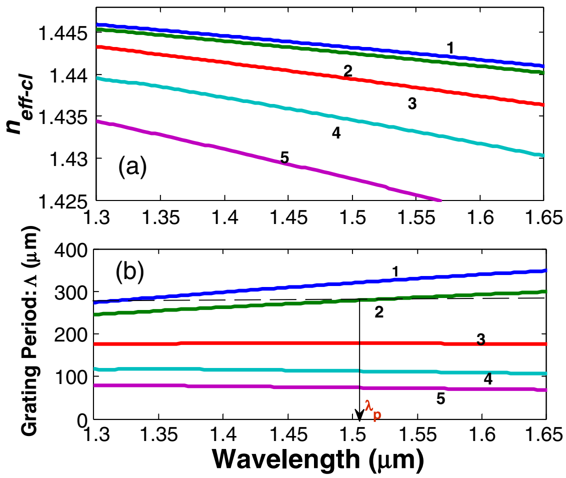

Fig. 4. (Color online) (a) Calculated effective indices of the first five cladding modes of the LPG with $D_{cl} = 30\,\mu m$ and surrounding material of liquid with $n_D = 1.3$ at 25 °C. (b) The phase-matching grating periods vs the coupling wavelengths for the first five cladding modes.

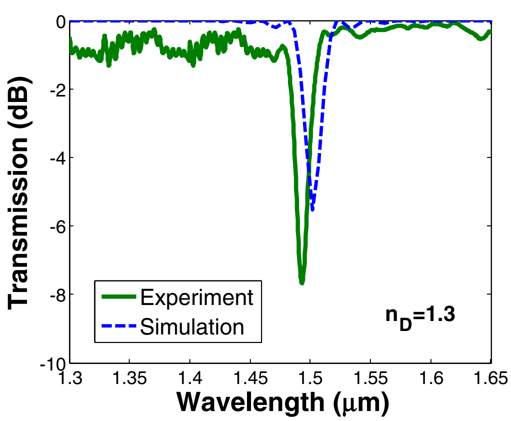

Fig. 5. (Color online) The experimental and simulated transmission spectra of the proposed ultrathin clad 2 cm-LPGs with the liquid having $n_D = 1.3$.

When the LPG cladding diameters are etched to 30 μm, the first five cladding modes are shown in Fig. 4(a), when surrounding material is liquid with $n_D = 1.3$, then the calculated phase-matched conditions as a function of the wavelength (λ) are shown in Fig. 4(b) as well. One can see that the variation of effective index of different cladding modes become much larger in the ultrathin clad LPG (UCLPG). It can be clearly seen from Fig. 4(b), that in the grating with the period of 280 μm the corresponding resonant wavelength λ_p is about 1.51 μm where the core mode and only the second cladding mode satisfy the phase matching coupling condition. Again, from the figure, there is only one resonant peak in a very wide wavelength band (>350 nm).

Figure 5 indicates the comparison of experimental and simulated transmission spectra of the device. The numerical calculation of the transmission spectra is solved by the

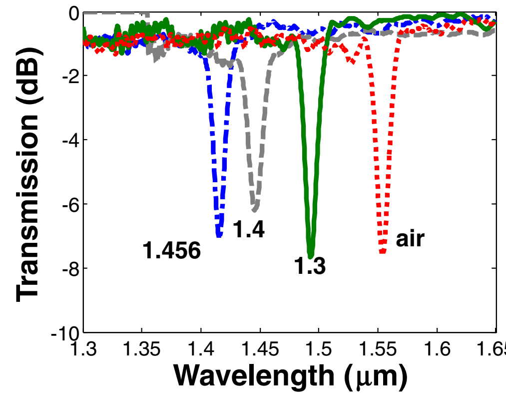

Fig. 6. (Color online) The measured transmission spectra of the proposed ultrathin clad 2 cm-LPGs when immersed in different surrounding optical liquids at 25 °C.

coupled mode equations of LPG reported in.[8] The calculated coupling coefficient (κ) of the original LPG was estimated below:

$$\kappa = \frac{\pi}{\lambda_p} \Delta n \cdot \eta \sim \frac{\pi}{1.5\,\mu m} \times 10^{-4} \times 0.2 \sim 0.042\ (\mathrm{mm}^{-1}) \quad (3)$$

where Δn is index modulation of about 10^{-4} and η is the fringe visibility between the core and the second cladding modes of LPG of about 0.2.[10] The linewidth of the peak of LPG can be directly solved by eq. (50) in ref. 10. It can be estimated that the -3 dB linewidth is about several to teens nm when the coupling strength under $\kappa L < \pi/2$ in a general LPG. In Fig. 5, there is a little mismatch between the experimental and simulated transmission results, which might be caused by error of estimations of material dispersions for the core and cladding in the commercial photosensitive LPGs. However, from the figure, it can be clearly seen that there are only a single resonant peak over a very wide wavelength range. It is important to note that avoiding the confusion of multiple resonant peaks of typical LPG can be more convenient for real time sensing. When the ultrathin cladding LPG immersed in different liquids at the fixed temperature 25 °C, the measured transmission spectra of the proposed LPGs are shown in Fig. 6. The transmission spectra with small loss (<1.0 dB averaged) can be easily tuned and the resonant peak obviously shifted to shorter wavelength when the refractive index of surrounding material increases. It is because of the m-order of the effective index of cladding mode $n^m_{\text{eff-cl}}$ increases when the refractive index of surrounding is raised, then the resonant peak λ^m_p moves toward the shorter wavelength due to the phase-matched condition of eq. (2). From Fig. 6, there is about 80 nm of wavelength shift for the variation of the refractive index of optical liquid from $n_D = 1.3$ to 1.456 and almost 150 nm wavelength shift for the refractive index of surrounding material varying from $n_D = 1$ to 1.456.

Figure 7 displays the calculated phase-matching grating period vs the coupling wavelength for the second cladding mode of 30 μm thin-clad, 2 cm long LPG when immersed in different surrounding optical liquids at 25 °C. From this

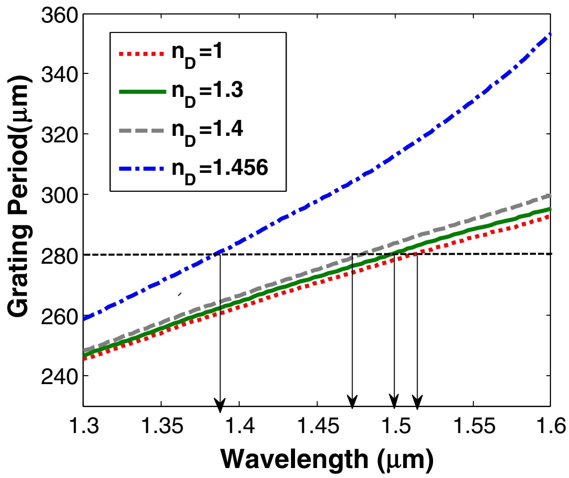

Fig. 7. (Color online) The calculated phase-matching grating periods vs the coupling wavelengths of the second cladding of LPG when immersed in different surrounding optical liquids at 25 °C.

figure, it is clearly seen that the wavelength shifts about 65 nm when the refractive index of surrounding varying from $n_D = 1$ to 1.4 and greatly shifts over 80 nm for n_D from 1.4 to 1.456. The reason of the phase matching wavelength does not change much for n_D from 1 to 1.4 is that under the strong guided situation the cladding mode field is almost confined in the first layer region due to large refractive index difference between first and second layers of claddings. Therefore, the change of resonant wavelength is not obvious for the $n_D = 1$ to 1.4. However, when the refractive index of surrounding material ($n_D = 1.4$ to 1.456) is very close to the silica, weakly guided situation makes the cladding mode field stretch into the second layer appreciably and the resonant wavelength of LPG will be strongly affected by a little variation of the refractive index of the surrounding material.

Figure 8 shows comparison of the simulated and experimental resonant wavelength peaks of the second cladding mode coupling for the proposed UCLPG as shown in Figs. 6 and 7. The numerical results are in fair agreement with the experimental results. There are a few reasons for the slight disagreement between the simulated and experimental data, which include: error estimation of material dispersion for the commercial photosensitive fiber, and non-precise control of temperature for the device. However, a very wide tunability demonstrated here is the most important out come of the study. Furthermore, the proposed UCLPG can be conveniently used as the temperature sensor because the refractive index of the optical Cargille liquids is temperature dependent ($dn_D/dT = -3.74 \times 10^{-4}/°C$) and the thermo-optic coefficient of silica based fiber is around 10^{-6}–$10^{-7}/°C$ that can be ignored.

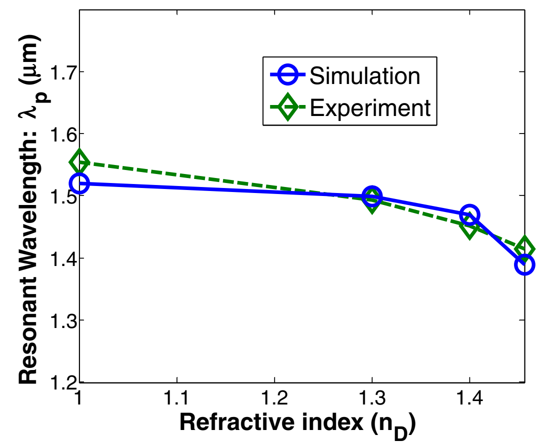

Fig. 8. (Color online) The comparison of the resonant wavelength peaks of simulated and measured results for the proposed UCLPG as shown in Figs. 6 and 7.

4. Conclusion

In this paper, an UCLPG filter with single resonant peak and very wide tunability has been demonstrated. Both experimental and theoretical analyses of the proposed device are accomplished. The transmission spectra of the device can be easily tuned by shifting the refractive index of cladding material. It is worth to mention that a single resonant peak in a wide wavelength band can reduce multiple transmission losses and the confusion in the spectral measurement. We believe that such features of UCLPG will be very useful in many applications for an ultra-wideband optical communications to cover the S^+–L bands and sensing applications.

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