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Modification of the refractive index response of long period gratings using thin film overlays

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Abstract

The response of a fibre optic long period grating (LPG) to the surrounding refractive index is shown to be modified by the deposition of a thin film of thickness of order 100nm onto the cladding. The LPG becomes sensitive to surrounding refractive indices greater than that of silica, and exhibits an enhanced sensitivity to external refractive indices lower than that of silica.

Fibre optic long period grating (LPG) devices are being developed and investigated for a range of uses in telecommunications and sensing systems[1,2]. The sensitivity of the transmission spectrum of a LPG to the refractive index of the surrounding material has been extensively investigated and has been exploited for a range of applications, including, for example, as a refractive index sensor[3], a chemical solution concentration sensor[4,5,6], to form a liquid level sensor[7], as a means of controlling the thermal response of the LPG[8] and for forming a tunable spectral filter[9]. While LPGs formed in silica based optical fibres are sensitive over only a limited refractive index range, typically from 1.4 to 1.45, and their response is not species specific, it has been shown that LPGs may be used for on-line monitoring of the concentration of aqueous solutions of materials especially in inaccessible or hazardous locations for industrial production quality control[6]. Concentrations of solutions of sodium chloride[6], calcium chloride[6] and ethylene glycol[5,6] have been measured. In this paper the use of a thin film overlay, deposited around the fibre, concentric with the LPG, to modify the range of refractive indices to which the LPG is sensitive is explored, extending their chemical concentration measurement capabilities.

An LPG is a periodic modulation of the refractive index of the core of an optical fibre. The period of the modulation is typically in the range 10 μm to 1000 μm. The correspondingly small grating wave-vector promotes coupling between co-propagating modes of the optical fibre. In the case of single mode fibre, the coupling takes place between the guided mode and co-propagating cladding modes. Efficient coupling is possible only at discreet wavelengths[10]. As the cladding modes suffer from high attenuation, the transmission spectrum of an optical fibre containing an LPG contains a number of attenuation bands, each corresponding to coupling to a different cladding mode, as is shown in figure 1.

The attenuation bands are centred on phase matching wavelengths governed by the expression[11]

$$\lambda_i = \left[n_{eff}(\lambda) - n_{cl}^{i}(\lambda) \right] \Lambda \qquad \textbf{(1)}$$

where $n_{eff}(\lambda)$ is the effective refractive index of the propagating core mode at wavelength λ_i, $n^i_{cl}\ (\lambda)$ is the refractive index of the ith cladding mode and Λ is the period of the LPG. The refractive index sensitivity of the transmission spectrum of an LPG arises from the dependence of the phase matching wavelengths upon the cladding mode effective index, which is dependent upon the refractive index of the surrounding material.

The form of the refractive index sensitivity of an LPG fabricated in B/Ge co-doped photosensitive optical fibre (Fibrecore PS 750) is shown in figure 2, where the shift of the central wavelength of the 5th attenuation band in the spectrum of the LPG when the submerged in a series of external media of different refractive indices is plotted. It is apparent the LPG's sensitivity lies predominantly within the range 1.400 to 1.456. The upper limit is imposed by the refractive index of the cladding material. For refractive indices above this limit there is no measurable wavelength response.

Previously we have shown that the transmission spectrum of an LPG is highly sensitive to the optical thickness of an overlay material deposited onto the optical fibre[12]. Here we aim to extend this study and investigate the effect of the presence of such an overlay material upon the response of the LPG to the surrounding refractive index.

A theoretical analysis of an LPG's response to the presence of the thin film overlay has been performed, allowing the dependence of the central wavelengths of the attenuation bands upon the refractive index of the surround material, both with, and without, a thin film overlay, to be determined. The effective refractive indices of the cladding modes were calculated as a function of wavelength and overlay thickness by considering the cladding/ overlay system as a stack of thin films and employing the transfer matrix method[13]. The effective refractive index of the propagating core mode was calculated using the weakly guiding approximation of Gloge[14]. Using the calculated dispersion of the core and cladding modes in equation 1, the central wavelengths of the LPG attenuation bands could be determined as a function of overlay thickness and refractive index, and of the surrounding refractive index.

Figure 3 illustrates the predicted response of the LPG to surrounding refractive index for different overlay thicknesses. The predicted external index response of an LPG with no overlay matches closely the form of the experimentally measured response, shown in figure 2. The graph shows that the presence of the film modifies the range of refractive indices to which the LPG is sensitive, while the sensitivity to lower refractive indices increases with increasing film thickness. It is also shown that, in the presence of the overlay, the LPG becomes sensitive to refractive indices higher than that of the cladding.

The Langmuir Blodgett technique allows the manipulation of materials at the molecular level. A monolayer of the organic material is spread on the subphase of pure water. The molecules are engineered such that one end of the chain is hydrophilic, while the other is hydrophobic. The monolayer is compressed to form an ordered film on the water subphase. A substrate passed through the air/water interface picks up a monolayer of thickness approx 3nm. Repeated passes through the interface allows a film to be built up one molecular layer at a time. High resolution control over the film thickness is achieved, ideal for waveguide applications. The technique may be readily adapted to facilitate uniform deposition of thin films onto a cylindrical structure such as an optical fibre[15,16].

The material deposited onto the fibres was tricosenoic acid [$CH_2=CH(CH_2)_{20}CO_2H$]. The material has a molecular length of 2.8 nm, and refractive index 1.57 at 633 nm[17]. The material was spread from dilute chloroform solutions (0.1 mg mL-1) onto the pure water subphase (conductivity 18 MΩ. cm) of one compartment of a Nima Technology Model 2410A LB trough, left for 20 minutes at ~20°C, and compressed at 0.5cm^2 s^{-1} (~0.1% s $^{-1}$ of total surface area). Deposition was achieved at a surface pressure of 30 mN m^{-1} and a transfer rate of 8 mm min^{-1}. The fibre containing the LPG was positioned vertically so its long axis was aligned with the dipping direction and was alternately raised and lowered through the floating monolayer at the air-water interface. This procedure gave a Y-type structure in which the amphiphilic molecules were packed head to head and tail to tail. Multiple passes through the film of molecular layer thickness 2.6nm were carried out to prepare LPGs with differing film thicknesses, and their response to immersion in Cargille oils of differing refractive indices monitored. The output from a tungsten halogen light bulb was coupled into the optical fiber containing the LPG. The output from the distal end of the fiber was incident on a PC interfaced CCD spectrometer (Ocean Optics S2000). The spectrometer offers a measurement range of 500 nm to 1100 nm, a resolution of 0.05 nm. The oil was maintained at a constant temperature of 25°C using a thermoelectric cooler.

The measured responses are shown in figure 4. The form of the results matches the theoretical prediction shown in figure 3, showing the enhancement of the sensitivity to low refractive indices lower than that of silica, and the development of sensitivity to refractive indices higher than that of the silica cladding.

To illustrate the influence of the presence of the thin film upon the performance of the LPG as a chemical concentration sensor, the response of the LPG to immersion in solutions of varying concentration of ethylene glycol was measured before and after the deposition of an overlay of thickness 90 nm. The results are shown in figure 5. A trend line (4th order polynomial) has been added to each data set as an aid to the eye. The LPG coated with a film of thickness 90 nm exhibits a larger wavelength shift with increasing concentration of ethylene glycol and concomitant increase in the surrounding refractive index[3,18]. The enhancement in sensitivity increases at higher concentrations, and is approximately double at 100% ethylene glycol concentration.

In summary, it has been shown, experimentally and using a simple theoretical model, that the deposition of a thin film of material with refractive index higher that that of the cladding onto an LPG can modify the LPG's sensitivity to the external refractive index. Enhanced sensitivity to refractive indices lower than that of the fibre’s silica cladding was observed, and the presence of the film resulted in the LPG exhibiting sensitivity to refractive indices higher than that of the cladding.

In the experiments discussed here, the optical properties of the material used to form the overlay were insensitive to the oil. However, it is possible to engineer LB films that change their refractive index in response to, for example, exposure to a particular chemical species[16], offering the prospect for developing a new chemical sensing capability.

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Figure Captions

Figure 1. Transmission spectrum of an LPG of period 400 μm, length 40 mm, fabricated in B/Ge co-doped photosensitive optical fibre with cut-off wavelength 650 nm.

Figure 2: Refractive index dependence of the central wavelength of the 5th attenuation band in the spectrum of the LPG detailed in figure 1.

Figure 3. Theoretical prediction of the response of an LPG to the external refractive index. ■ with no overlay, + overlay thickness 75 nm and ▲overlay thickness 125 nm. The overlay refractive index is assumed to be 1.57 in the calculations.

Figure 4. Experimentally determined surrounding refractive index response of the 5th attenuation band in the spectrum of the LPG to the external refractive index. ■ with no overlay; ♦ with 90nm overlay; ▲ with 120 nm overlay and − with overlay thickness of 150nm

Figure 5. Experimentally determined response of the 5th attenuation band in the spectrum of the LPG to the change in concentration of ethylene glycol and refractive index with ■ no overlay; ♦ with overlay thickness 90nm

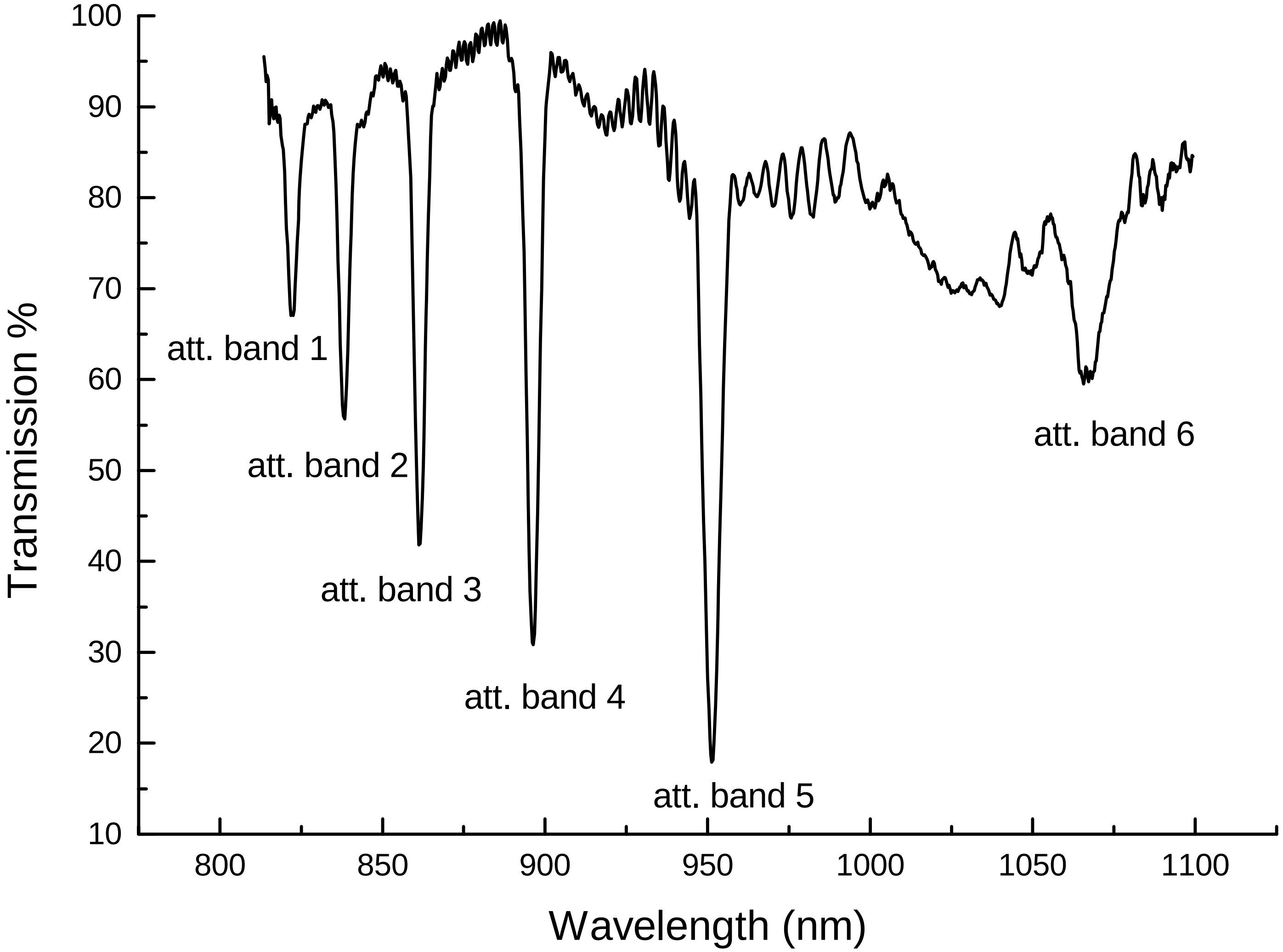

100
90
80
70
60
50
40
30
20
10
Transmission %
800
850
900
950
1000
1050
1100
Wavelength (nm)
att. band 1
att. band 2
att. band 3
att. band 4
att. band 5
att. band 6

Figure 1

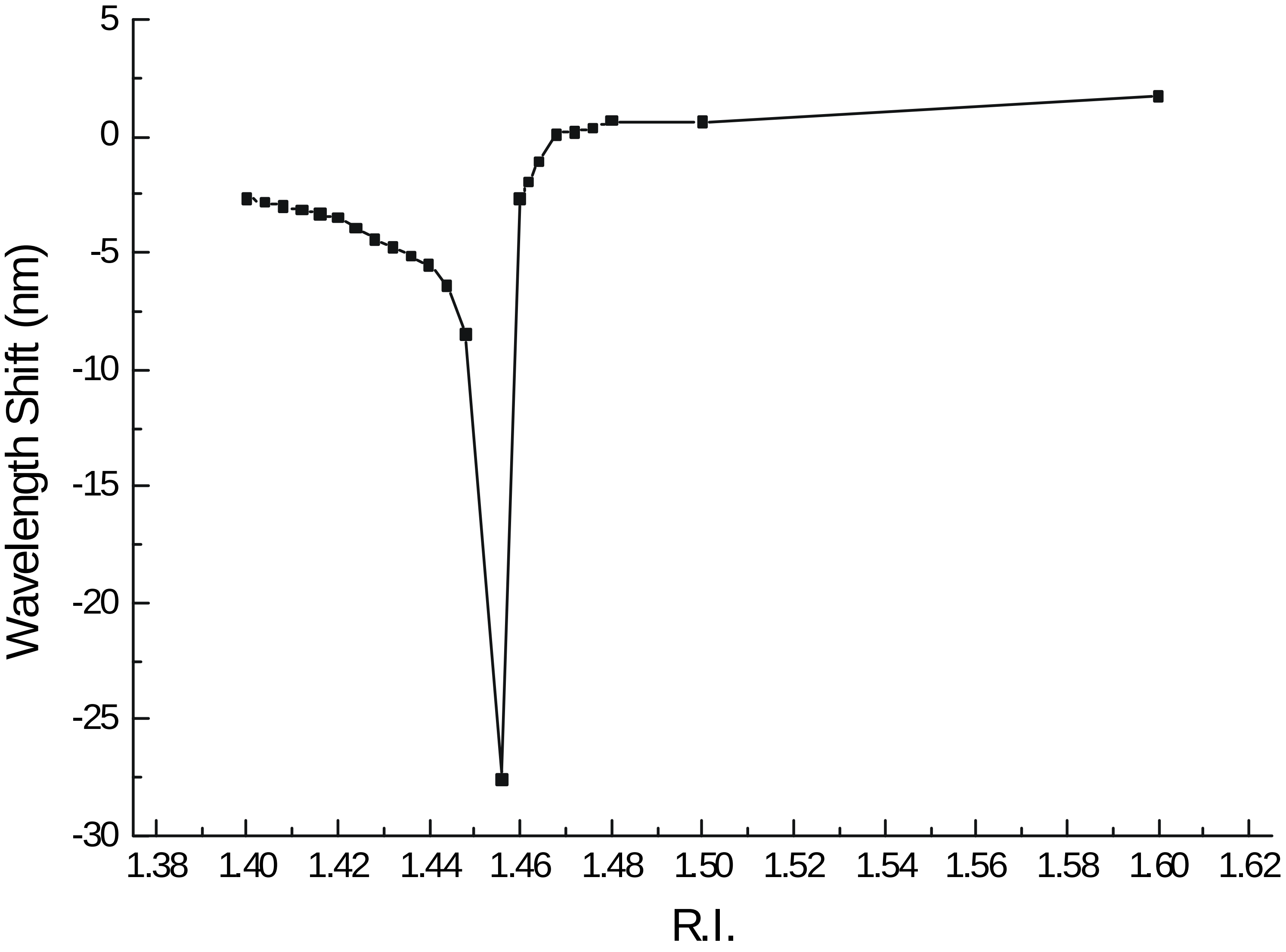
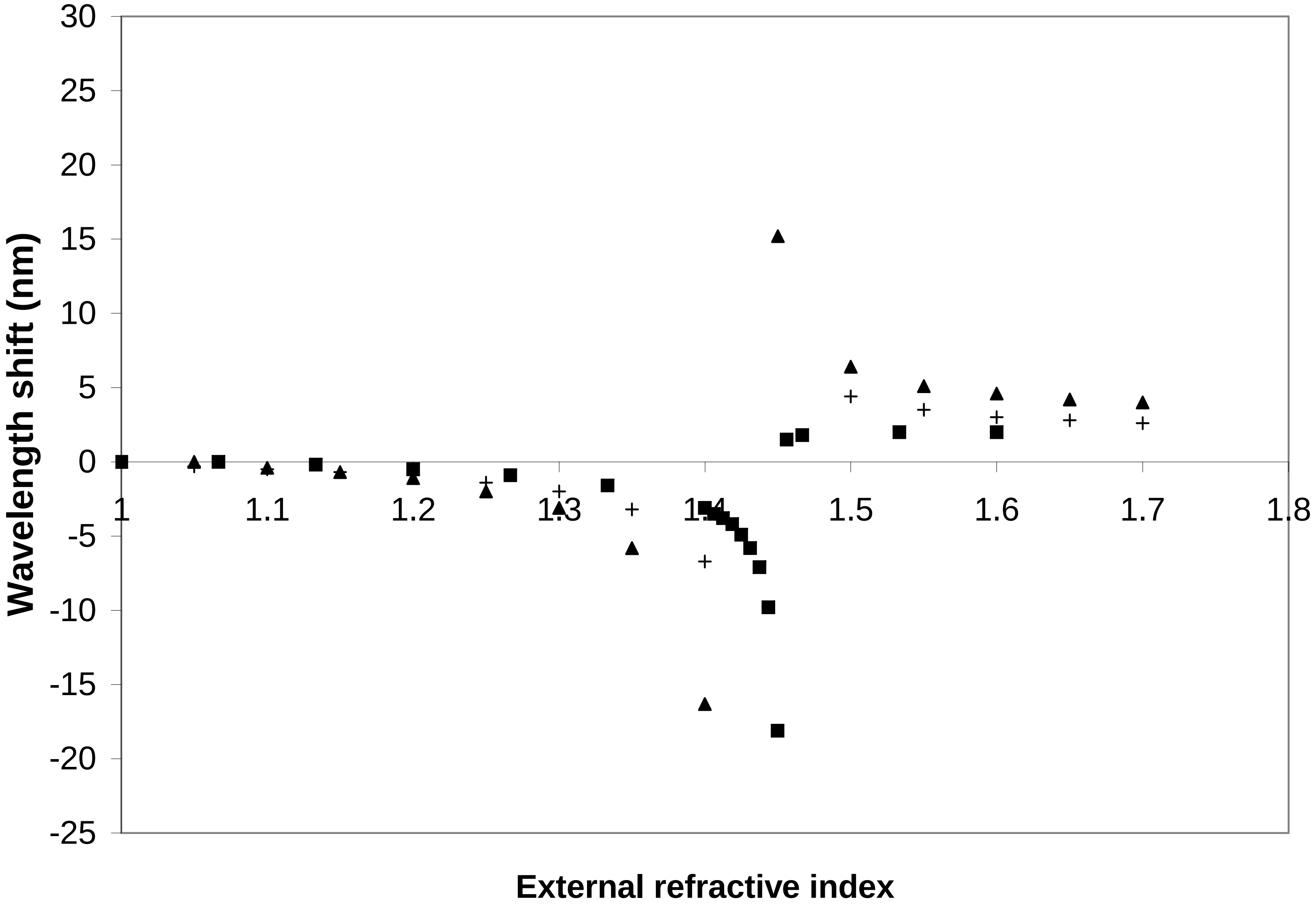

5
0
-5
-10
-15
-20
-25
-30
Wavelength Shift (nm)
1.38
1.40
1.42
1.44
1.46
1.48
1.50
1.52
1.54
1.56
1.58
1.60
1.62
R.I.

Figure 2


30
25
20
15
10
5
0
-5
-10
-15
-20
-25
Wavelength shift (nm)
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1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
External refractive index

Figure 3

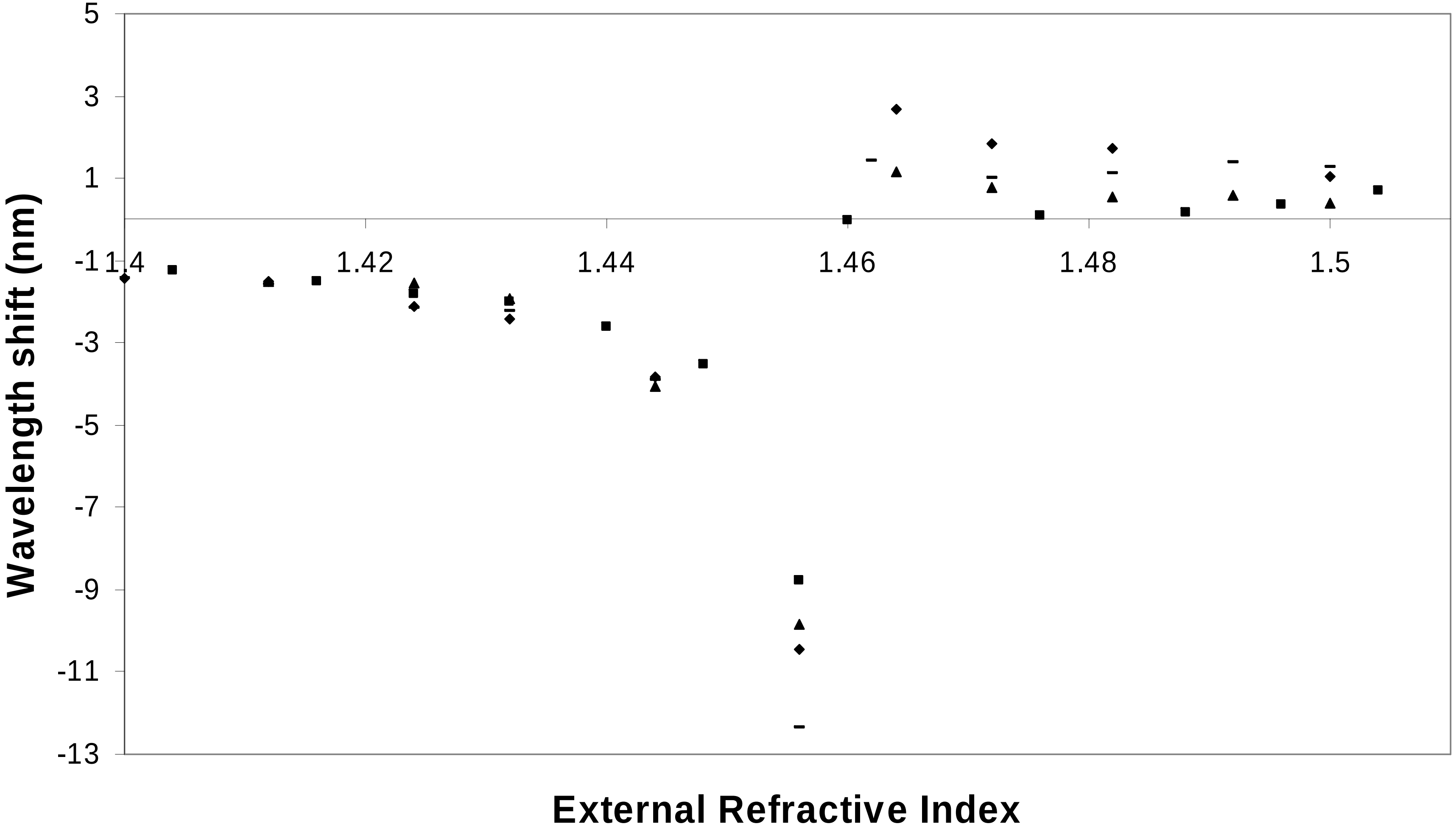
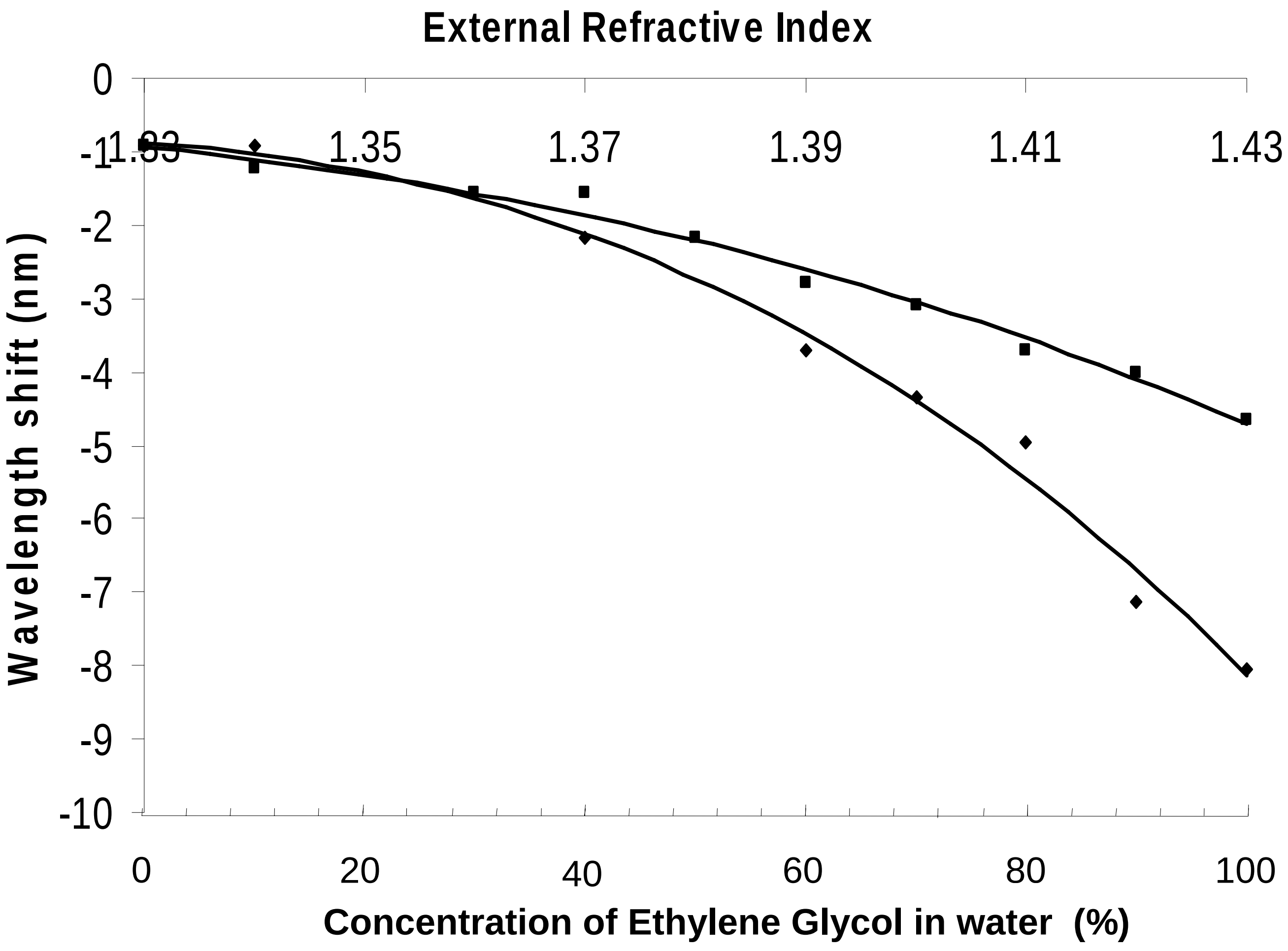

5
3
1
-1
-3
-5
-7
-9
-11
-13
1.4
1.42
1.44
1.46
1.48
1.5
Wavelength shift (nm)
External Refractive Index

Figure 4


External Refractive Index
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1.35
1.37
1.39
1.41
1.43
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
Wavelength shift (nm)
0
20
40
60
80
100
Concentration of Ethylene Glycol in water (%)

Figure 5