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Cryogenic Temperature Response Of Fibre Optic Long Period Gratings

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Abstract

The thermal response of the attenuation bands of an optical fibre long period grating was monitored over a temperature range 4.2K to 280K. A linear dependence of the central wavelength of the band, of gradient 0.2 nm/K was observed over the range 77K to 280K. A measurable wavelength shift was observed at temperatures as low as 20K.

Keywords: Fibre optic sensor. fibre grating, long period grating, temperature, cryogenic.

Fibre optic long period gratings (LPGs) exhibit a number of unique features which make them attractive candidates for in-line filtering applications in telecommunications, and for application as sensor elements[1]. A long period grating consists of a period 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 to only a subset of the cladding modes[2]. As the cladding modes suffer from high attenuation, the transmission spectrum of an optical fibre containing a LPG contains a number of attenuation bands, each corresponding to coupling to a different cladding mode.

The phase matching wavelengths are governed by the expression[3]

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

where $n_{eff}(\lambda)$ is the effective refractive index of the propagating core mode at wavelength λ, $n^{i}_{cl}(\lambda)$ is the refractive index of the ith cladding mode and Λ is the period of the LPG. Figure 1 shows the transmission spectrum of a LPG of period 400μm, length 40mm, fabricated in B-Ge codoped fibre with a cut off wavelength 650 nm, exhibiting the characteristic attenuation bands.

Environmental parameters that differentially change the effective indices of the modes of the core and cladding, or that change the period of the LPG, result in a shift in the central wavelengths of the attenuation bands, facilitating the development of sensor systems, or tuneable filters. The sensitivity of LPGs to environmental parameters is influenced by the period of the LPG, by the order of the cladding mode to which coupling takes place and by the composition of the optical fibre[4,5]. This combination of influences allows the fabrication of LPGs that have a range of responses to a particular measurand - a single LPG may have attenuation bands that have a positive sensitivity to a measurand, others that are insensitive to the measurand and others with a negative sensitivity[6].

The temperature response of fibre optic long period gratings has been extensively studied. LPGs with temperature insensitive attenuation bands have been demonstrated in LPGs with short period (40μm)[3]. LPGs fabricated in standard telecommunications optical fibre exhibit temperature sensitivities in the range 3 nm/100 °C to 10 nm/100 °C[6], an order of magnitude larger than the temperature sensitivity of FBG sensors. For the fabrication of high resolution temperature sensors, or to create widely tuneable filters, a number of techniques for further enhancing the sensitivity have been reported, including the use of fibres of different composition[4,5], different geometries[7] and the use of polymer coatings[8].

In this paper the thermal response of the LPG transmission spectrum is investigated at temperatures in the range 4.2 K to 300 K. The thermal response of fibre Bragg gratings at cryogenic temperatures has been investigated previously[9,10,11], showing that at temperatures below approximately 100 K, the spectrum is temperature insensitive. To the authors' knowledge, there have been no previously reported studies of the response of LPGs at cryogenic temperatures.

An LPG, with parameters described previously, was fabricated by exposing the fibre to the output of a quadrupled Nd:YAG laser operating at 266 nm through an amplitude mask of period 400μm. The transmission spectrum is shown in figure 1. The use of a fibre with a low cut off wavelength results in the attenuation bands of interest being located within the wavelength response of silicon detectors. The transmission spectrum was monitored by coupling the output from a white light source, a Tungsten Halogen lamp, into the optical fiber containing the LPG and coupling the output from the distal end of the fiber into a PC interfaced CCD spectrometer (Ocean Optics S2000). The spectrometer disperses the spectrum over the 2048 pixels of the CCD linear array, offering a measurement range from 500 nm to 1100 nm. The integration time may be controlled to optimise the SNR, the minimum integration time being 1 ms. The central wavelengths of the attenuation bands were determined using a polynomial fit to the spectral data, giving a resolution of 0.02 nm. The LPG was inserted into a cryostat and mounted such that it remained straight throughout the experiment to avoid bend induced changes in the transmission spectrum[12]. This was achieved by placing the region of fibre containing the LPG within a glass tube of internal diameter 1 mm. The LPG spectrum and the output from Rhodium Iron temperature sensors were monitored as the cryostat was cooled from room temperature to 4.2 K, over a period of 2 hours. Monitoring the response during both cool down and warm up indicated that the response was reproducible. The cryostat consists of an outer vacuum jacket (OVC), a sample space which is a liquid Helium (LHe) reservoir and a cylindrical liquid Nitrogen (LN_2) jacket which is built into the OVC and surrounds the LHe can. The cryostat was pre-cooled by filling the LHe can and the LN_2 jacket with LN_2. The system is typically left overnight in this state. After this period, any LN_2 remaining in the LHe can is blown out using He gas and the sample space is cooled to the magnet operating temperature ($T \leq 4.2$K) by filling with LHe.

The measured response is shown in figure 2, where the wavelength shift of attenuation band 5 (corresponding to coupling to the 5th order cladding mode) is plotted as a function of temperature during cool down from 280 K to 4.2 K. The response is approximately linear down to 77K, with gradient 0.2nm/K. Below 77K the temperature sensitivity decreases, but, as shown in figure 3, the LPG still displays a measurable thermal sensitivity at temperatures as low as 20K. The feature between 220 and 250 K is a result of a restriction of the Nitrogen flow which occurred at 200 K, before the Nitrogen had condensed, and resulted in a rapid increase in temperature during which the LPG and the Rhodium Iron temperature sensors were not in thermal equilibrium. The restriction was removed, and cooling recommenced. The feature at 80K is a result of a rapid warm up that occurred as the liquid Nitrogen was blown out.

FBGs have been shown previously to be largely temperature insensitive below 100K[11]. The reason for the extended range exhibited by the LPGs is the dependence of the coupling wavelength upon the difference between the index of the core and cladding. The doping of the core of the fibre with Boron and Germanium to enhance photosensitivity might be expected to provide a significant differential thermal response of core and cladding.

In summary, the thermal response of a LPG has been monitored from room temperature to 4.2 K. The LPG attenuation bands exhibited linear temperature dependence from room temperature down to 77K. Below 77K, a thermal response was measurable to below 20 K.

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Figure Captions

Figure 1. Transmission spectrum of a 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. Temperature response of the LPG over the full measurement range, recorded while cooling the cryostat from 280 K to 4.2 K.

Figure 3. Temperature response of the LPG over the temperature range 45 K to 4.2 K. The LPG exhibits a measurable thermal response at temperatures down as low as 20 K.

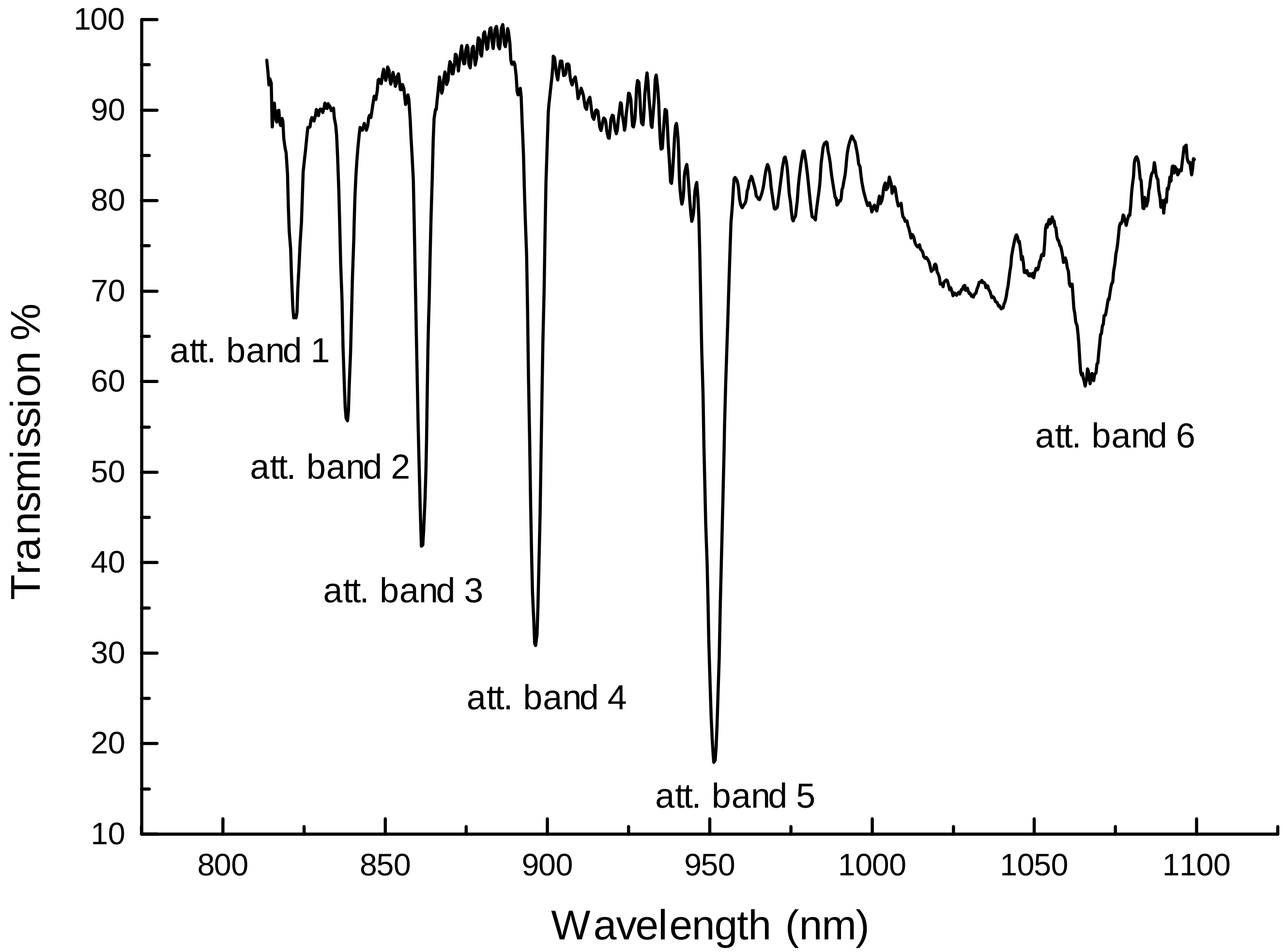

100
90
80
70
60
50
40
30
20
10
Transmission %
800
850
900
950
1000
1050
1100
Wavelength (nm)
att. band 1
att. band 2
att. band 3
att. band 4
att. band 5
att. band 6

Figure 1

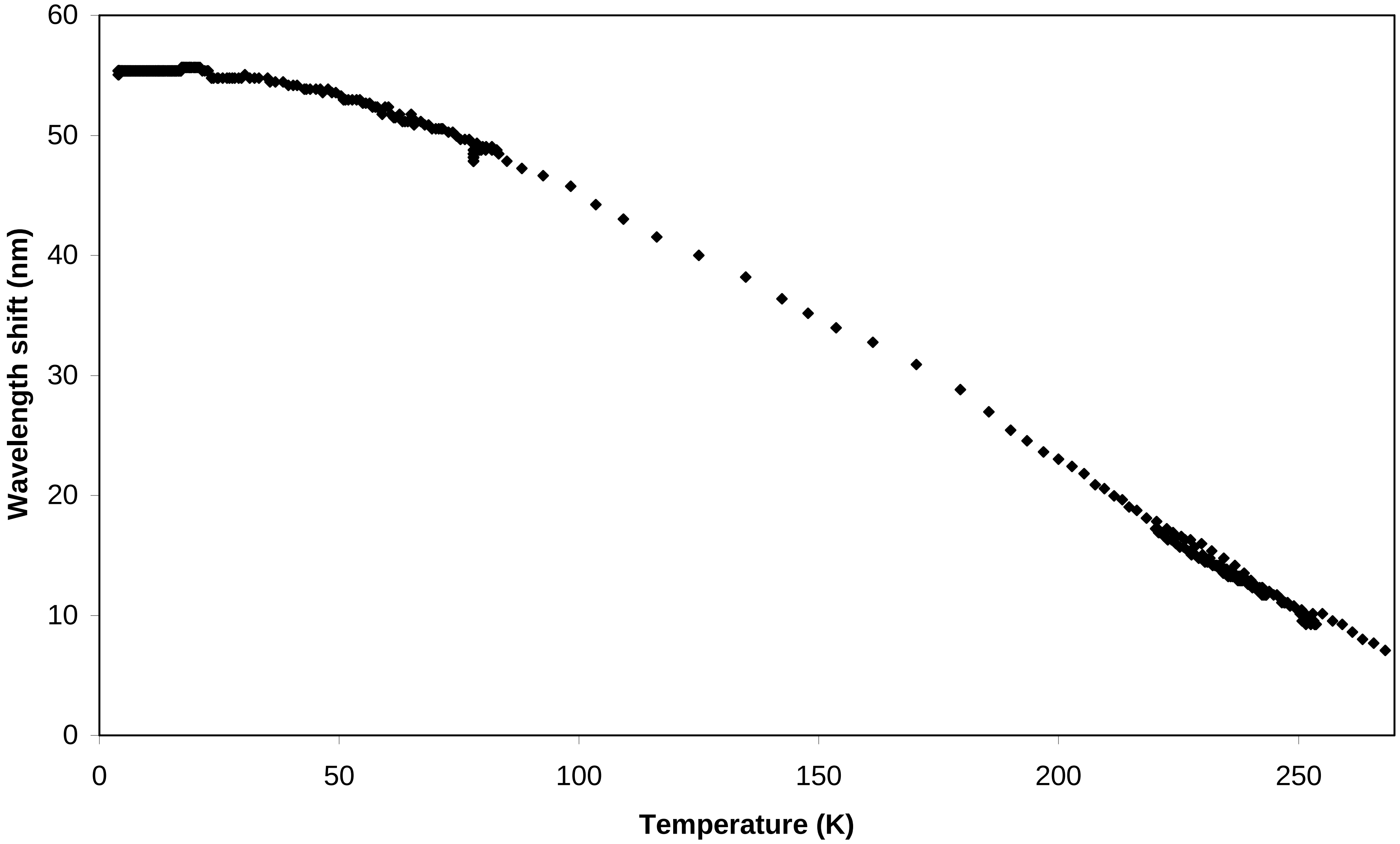
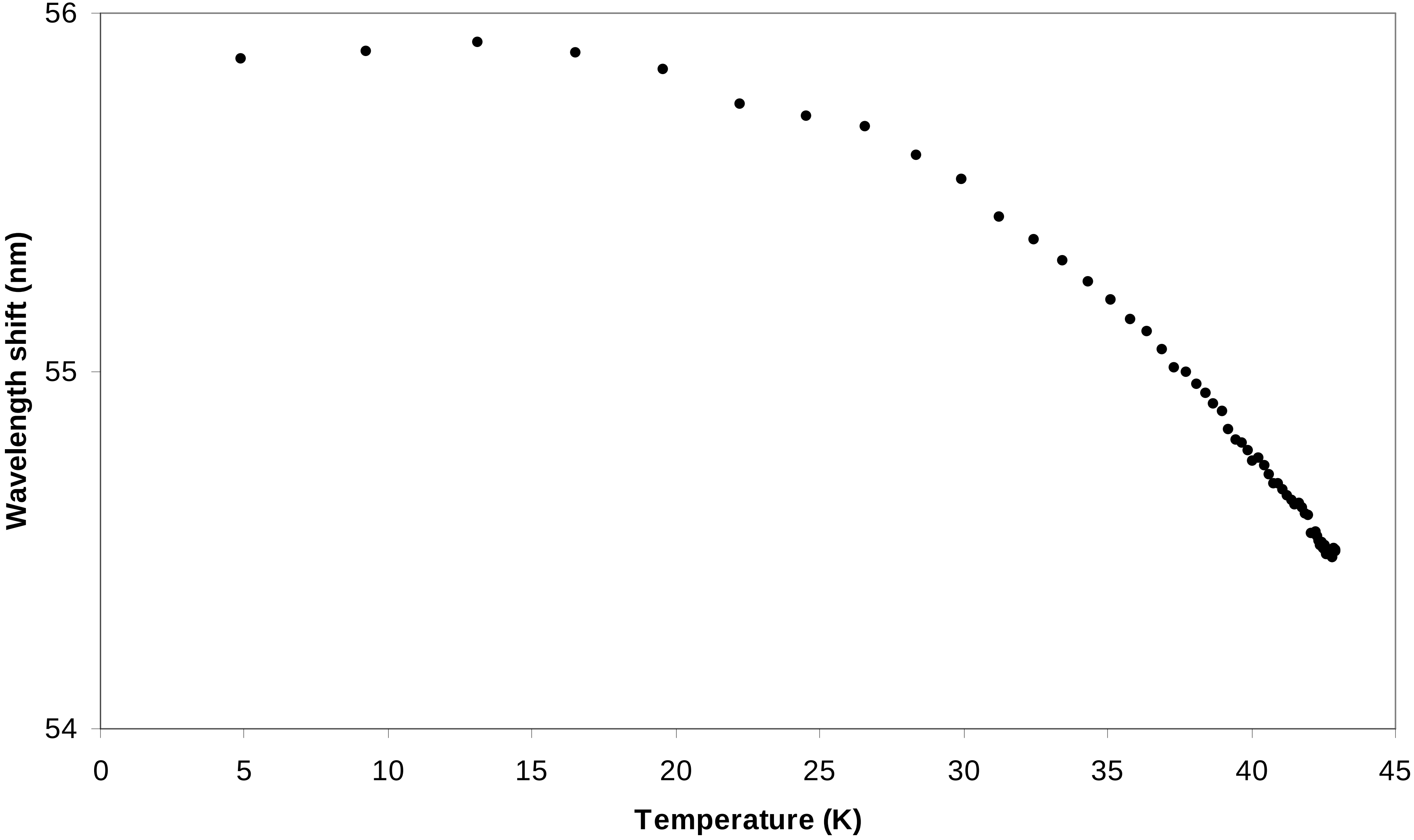

Wavelength shift (nm)
0
10
20
30
40
50
60
Temperature (K)
0
50
100
150
200
250

Figure 2

Figure 3.


56
55
54
0
5
10
15
20
25
30
35
40
45
Wavelength shift (nm)
Temperature (K)