Fabrication of high rejection, low loss, filters by the concatenation of broadly chirped fibre Bragg gratings

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ABSTRACT

Single- and multiple-bandpass filters with broad, high-rejection stopbands and narrow, low-loss passbands are significant components for fibre networks. Hitherto, this combination of characteristics has proved elusive using in-fibre grating techniques. Here, we report the realisation of practical single-passband filters synthesised from concatenated chirped broadband fibre gratings written holographically in a highly photosensitive fibre. Practical, low-loss (<2dB), single-passband fibre Bragg grating transmission filters have been fabricated with >30dB out-of-band rejection over a 25nm spectral width.

Keywords: Fibre Bragg grating, bandpass filter, light transmission and rejection.

2. INTRODUCTION TO FIBRE GRATING BANDPASS FILTERS

The dramatic increase in fibre photosensitivity due to the use of fibre doping[1] and hydrogen-loading[2,3] has opened up the way for the fabrication of high reflectivity broadband gratings. The broadest bandwidth gratings[4] are chirped i.e. the grating period varies along the grating; such gratings have been fabricated in fibre by direct-write holographic methods[5,6] since 1992. One of the most flexible approaches to fabricating chirped gratings uses the interference of wavefronts with unequal radii of curvature[7,8]. It is now possible to induce refractive index changes[9] in excess of 10^{-2} thus fabricating ultra-strong fibre gratings[10,11,12,13,14,15,16,17] that can achieve rejection levels of >80dB. Such strong gratings become important when very high suppression of interchannel crosstalk is required. The advantage in applying fibre grating technology to the production of bandpass filters lies in the system compatibility and eventual low production costs.

Single and multiple-passband filters with narrow, low-loss, passbands and broad, high rejection, stopbands are important components for fibre networks and to date this combination of features has been difficult produce using in-fibre gratings. This paper presents what we believe to be state-of-the-art results for broadband filters and draws attention to various design issues involved in fibre choice and predictions of filter lifetime and passband stability. We report the realisation of practical single-passband filters from the concatenation of two or more chirped fibre gratings written holographically in germania-doped or boron/germania-codoped hydrogen-loaded fibres. Rejection levels exceeding 30dB have been reached for single gratings with bandwidths >10nm, structures of this type have been used as the building blocks to synthesise a range of filters. Although interferometric techniques have been used to fabricate the filters described in this paper it is envisaged that when design issues have been resolved a phase mask could be produced to fabricate multiple identical structures.

The highest rejection levels have been obtained using hydrogen-loaded boron/germania-codoped fibres we have found that the accompanying short-wavelength loss, caused by the grating providing a coupling mechanism between the guided and lossy transmission modes, imparted on the passband region is generally too high (>2dB) to be acceptable in filter fabrication. To avoid this loss penalty germania-doped fibres were used instead despite a consequent small decrease in the fibre photosensitivity.

To increase the bandwidth of the stopband three gratings were concatenated together. The gratings were fabricated in germania-doped fibre to give low loss over the passband and in boron-germania-codoped fibre to give maximum rejection at the short-wavelength side of the filter. A single passband structure which exhibits >30db out-of-band rejection over 25nm, with an ~1nm passband at 1549nm was realised. This general method can be extended to realise further filter functions in a practical, compact format.

3. PRACTICAL REALISATION OF FIBRE GRATING BANDPASS FILTERS

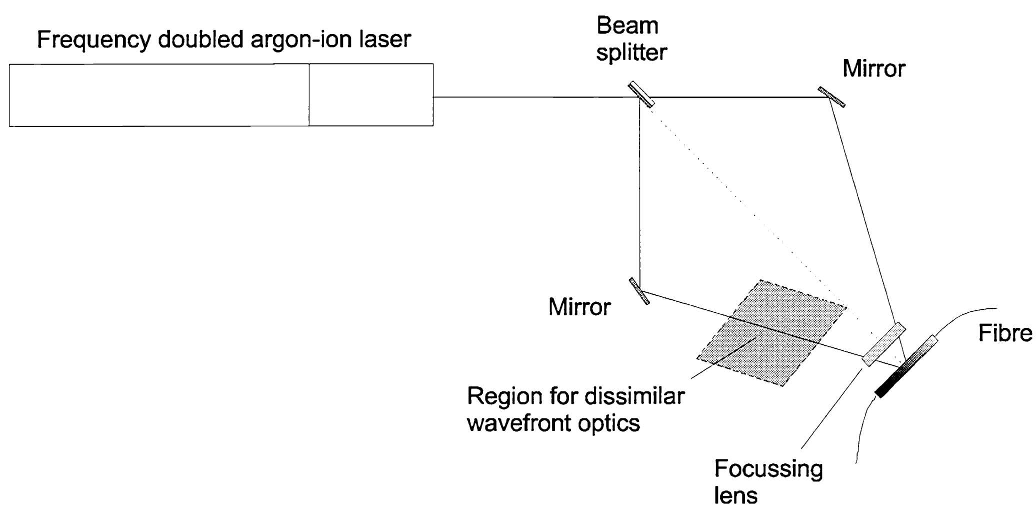

Figure 1 Interferometric approach to chirped fibre grating fabrication.

The chirped gratings were fabricated holographically[4,7] with the output of a frequency-doubled argon-ion laser using a traditional kite-shaped interferometer. A controllable amount of chirp was introduced by two vertically mounted cylindrical lenses of the same focal length in a slightly detuned 1x1 telescope configuration, Figure 1. The chirp rate and consequently the bandwidth was altered by changing the amount of the telescope detuning. The gratings were monitored over a large bandwidth using an erbium-fluorescence source and an optical spectrum analyser (OSA). At specific wavelengths the rejection level was also measured using a tunable laser and an OSA which increased the dynamic range of the measurement. The fibres used were either highly doped with germania (9%) or were codoped with boron and germania. Prior to exposure the fibres were soaked in hydrogen for at least seven days at up to 200 atmospheres pressure and room temperature. A single chirped grating, ~6mm long, was written at one end of a 3cm long stripped section of fibre. The rejection level was monitored during the exposure and the laser beams blocked when the gratings stopped increasing in strength. The interferometer was then realigned to increase the wavelength of the gratings fabricated. The fibre was translated and a second grating written at the other end of the stripped section of fibre. By calculating the angles between the two interfering beams the two gratings written exhibited the appropriate wavelength separation to result in the creation of a passband region between the two stopbands.

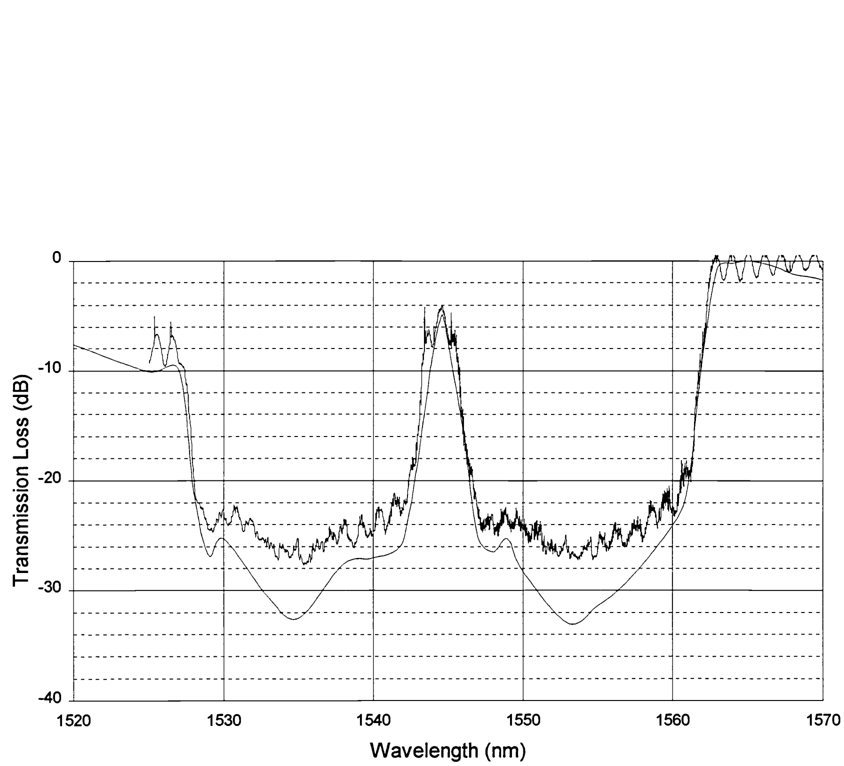

Figure 2 Bandpass filter fabricated using two chirped gratings.

Figure 2 shows an example of a bandpass filter fabricated in a germania-doped fibre comprising of two ~6mm long gratings. The filter has a stopband of ~35nm and a passband of 2.4nm. The rejection over the stopband of the filter exceeds 22dB measured from the peak of the passband. The thicker line shows the filter response measured using a tunable laser and a photodiode; the 2dB ripple is a characteristic of the tunable laser and not of the filter. The thinner line is a profile taken later using a tunable laser and OSA. The two profiles differ slightly because, although the combination of the tunable laser and photodiode gives a simple, higher resolution, measurement of the filters spectral response, the background noise level originating from laser sideband transmission through the passband and through regions beyond the filter stopband is sizeable in the measurement of low transmission in the stopband. Using an OSA avoids this issue but incurs a time or wavelength resolution penalty.

The primary contribution to loss on the passband is from coupling to lossy radiation modes in the fibre, there is also some loss from OH^- absorption but this can be significantly reduced using deuterium in the loading process. The loss from radiation modes is increased by a slight tilt on the fringes that is caused by using dissimilar interfering wavefronts to produce the chirp. The loss increases with the amplitude of the refractive index change and occurs over the region where the passband is situated. Increasing the numerical aperture (NA) of the fibre reduces the loss because it increases the guiding strength of the fibre. The number of gratings used could also be increased since that would limit the maximum refractive index changes required.

The interplay between loss, bandwidth and reflectivity[18] requires that a balance be struck between the three to give an optimum result. The type of filter required will affect the range choice by dictating the bandwidth and reflectivity and so limiting the choice of fibre that can be used to achieve these specifications. For example, if high rejection is required over a wide bandwidth a B/Ge-codoped fibre may be selected for its higher photosensitivity. But as a consequence of a lower NA the induced losses will be higher. One possibility is that two or three gratings may be fabricated in different types of fibre which can then be spliced together. Smaller bandwidth gratings in high NA fibre could be used to provide the high wavelength stopband so keeping the loss over the passband to a minimum whilst very strong broad bandwidth gratings could be fabricated in boron/germania-codoped fibre to form the short wavelength stopband.

An example of such a grating is shown in Figure 3. The high wavelength grating was fabricated in germania-doped fibre to minimise loss on the passband whilst the short wavelength grating was written in boron/germania-doped to maximise the rejection-bandwidth product. The spectrum shown was measured using an OSA and an erbium fluorescence source but when measured using a tunable laser and OSA the filter showed -32dB rejection over 10nm at the high wavelength side and up to -39dB rejection over 30nm at the short wavelength side.

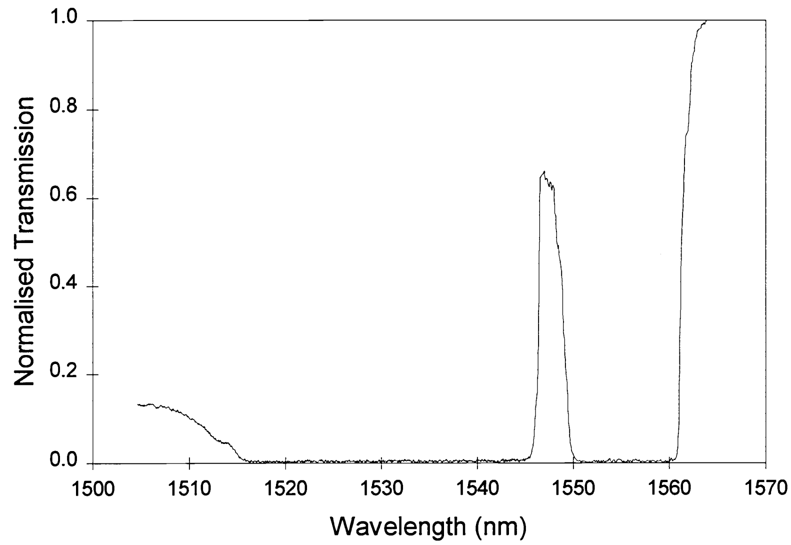

Figure 3 Optical Spectrum Analyser measurement of a grating made in high Ge and B/Ge doped fibre. -32dB rejection at high wavelength side, -39dB rejection at the low wavelength side when measured with tunable laser.

4. LIFETIME CONSIDERATIONS

Recently, there have been intensive studies of lifetime and thermal stability of linear structure fibre gratings[19,20,21,22,23,24]. However, these studies have concentrated on relatively weak gratings compared to those used in the work described above. To verify the effect of temperature ageing on structures relevant to this work a selection of chirped gratings where isothermally annealed. The gratings were all ~10nm and were written in three different types of fibre - standard telecommunication, high Ge-doped and B/Ge-codoped. The isochronal annealing took the gratings from room temperature to 705°C in 17 increments of 40°C each lasting 30 minutes.

Figure 4 shows the effect of isochronal annealing on three different chirped gratings. The initial reflectivities of the gratings the were 85%, 82% and 95% for standard, high Ge-doped and B/Ge-codoped fibre respectively. The amplitude of the UV-induced index changes required for these structures approached a maximum ~2×10^{-3} for the gratings written in boron/germania. As the temperature was increased the bandwidth and reflectivity values of each grating were monitored and this data was converted into values for the amplitude of the refractive index modulation were calculated using a transfer matrix modelling technique[25,26].

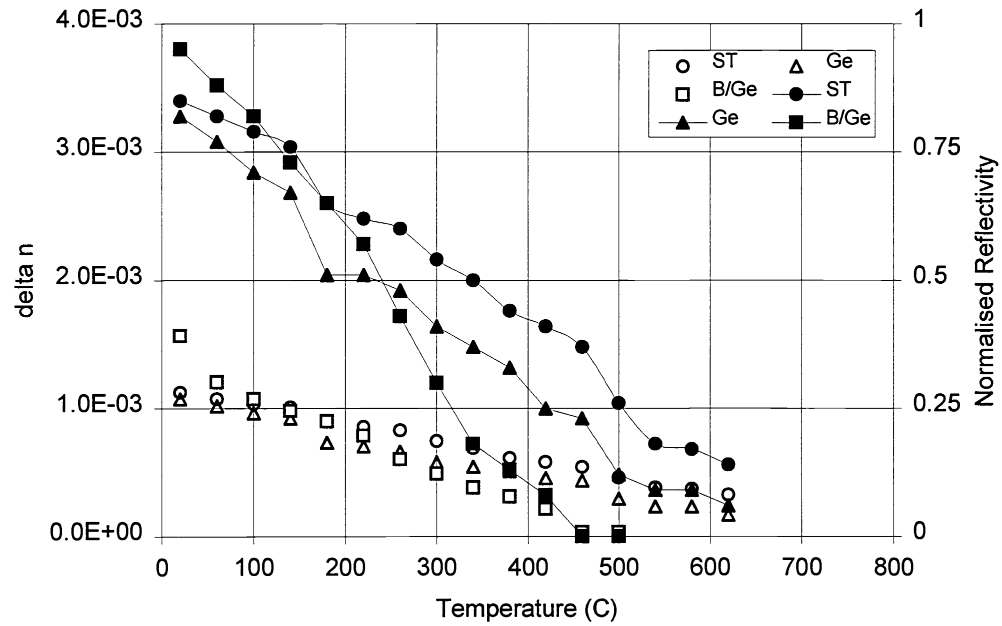

Figure 4 Change in the amplitude of the induced index modulation (delta n) and the change in normalised reflectivity (solid points) of chirped gratings of ~10nm bandwidth during isochronal annealing.

The chirped gratings showed a significant variation in reflectivity as the temperature. The gratings fabricated in standard telecommunications fibre were the most thermally stable and showed the slowest decay in reflectivity. Unfortunately the most photosensitive fibre was the least thermally stable. Although starting out the strongest the gratings written in boron/germania-codoped fibre showed the fastest decay in reflectivity and refractive index modulation and had totally disappeared by 475°C. In consequence, where long component lifetimes are required for high reflectivity devices B/Ge-codoped fibre which initially appeared to be the optimum fibre in terms of photosensitivity may not be the most suitable.

The bandwidths of chirped gratings, which are predominantly properties of the device structure and not the index change, did not change significantly during annealing. This is useful for the fabrication of filters since although the rejection will change the general shape of the response should be maintained.

The isochronal annealing showed that chirped gratings are much more susceptible to changes in reflectivity than uniform-period gratings due to shorter interaction lengths for each wavelength; high temperature accelerated ageing will therefore lead to a noticeable drop in the rejection levels. Either operating temperatures must be limited or some way of extending the device lifetimes must be found. One option is to write longer gratings to increase the interaction lengths for each wavelength. Alternatively, multiple gratings with smaller bandwidths could also be used to the same effect. Filters comprising of gratings fabricated in two different fibres will exhibit non-uniform ageing and this must also be taken into account. The thermal decay of a grating, in a certain fibre with a given set of parameters, is repeatable so can be built into the filter design.

5. CONCLUSIONS

The concatenation of chirped fibre Bragg gratings has been used to fabricated broadband single passband filters. Stopbands exceeding 30dB over a >25nm bandwidth have been demonstrated with corresponding passbands of 2-3nm where the loss within the passband depends on the structure and strength of the component gratings as well as on the choice of fibre. The thermal evolution studies on gratings in standard telecommunication, Ge-doped and B/Ge-codoped fibres, showed that for any one grating the thermal sensitivity and stability were markedly dependent upon the type of fibre used. The gratings fabricated in B/Ge-doped fibre were thermally the most sensitive showing a rapid decay in reflectivity leading to the eventual disappearance of the gratings at a temperature of ~450°C. The slowest rate of decay was shown by gratings fabricated in standard fibre. To maintain very high rejection bandwidths over reasonable lifetimes, the use of such filters will be restricted to low temperatures unless the structures can be made longer or higher refractive index changes can be induced.

6. ACKNOWLEDGEMENTS

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