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Chirped Fibre Bragg Gratings Fabricated Using Etched Tapers

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Abstract: We have demonstrated a technique capable of controllably producing fibre Bragg gratings with any arbitrary chirp profiles. The technique involves making a taper on the outer cladding of a section of fibre by differential etching along the length of the fibre. A grating is then written over the taper in the usual manner. A strain gradient develops over the taper when a tension is applied to the fibre and this strain gradient is used to introduce a chirp in the gratings. The chirp can be introduced either during or after grating writing. Tension can be used to tune the central wavelength and chirp the gratings if desired. Linearly chirped gratings with bandwidth up to 4.8nm have been produced to demonstrate the controllability of the technique. These gratings are ideal for use in dispersion compensation and optical pulse shaping.

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Background: There has been a surge of interest in photosensitive fibre Bragg gratings, chiefly due to their ease of fabrication and numerous applications such as reflectors for fibre lasers (particularly single frequency fibre lasers), as filters, in fibre sensors etc. The strong dispersion of a chirped fibre Bragg grating has been used to compensate for dispersion in an optical fibre link [1,2] and for optical pulse shaping [3]. Such gratings can also be used as broad band reflectors in fibre and semiconductor lasers.

There are chiefly two ways to make chirped gratings; post-chirping a uniform grating or introducing a chirp during the writing process. As the Bragg wavelength $\lambda_g = 2n_{eff}\Lambda$, where n_{eff} is the effective index of the propagating optical mode and Λ is the grating pitch, a grating can be chirped by varying either the effective modal index or the grating pitch along its length.

To introduce a chirp into the grating while writing, there are several techniques which have been demonstrated, *e.g.* varying the effective modal index using a second exposure [1], by tapering the fibre core [4], varying the grating pitch by bending the fibre [5], by using a chirped phase mask [6], by focusing the two interfering beams differently [7] and, most recently, by adjusting fibre strain while scanning a writing beam along the fibre [8]. Chirps as large as 44 nm [7] have been demonstrated, but there are usually many difficulties in obtaining a controllable chirp. For dispersion compensation and pulse shaping, gratings with a relatively small chirp of several nanometres but with very well defined chirp profile are required. The technique using a chirped phase mask [6] has been able to give a good chirp control, but, so far, only stepped chirp profiles can be produced.

A temperature [9] or strain gradient [10, 11] can be applied to post-chirp a uniform grating; the gradients vary both the effective modal index and the grating pitch along the length of the gratings. Good controllability has been demonstrated with a temperature gradient [9], but a high temperature is required to obtain a large chirp ($\Delta\lambda_g/\lambda_g$ = 8.86×10^{-6} ΔT, for 1 nm chirp at 1.55 μm one needs ΔT = ~70 °C). It is also very difficult to obtain chirp profiles other than linear, and active temperature gradient control is required in the final device. Good strain-chirped gratings have been demonstrated recently using a cantilever [2,11], but the method is potentially polarisation sensitive due to the bend-induced birefringence and it is also difficult to package the final device because of their large size.

Very recently, a technique for fabrication of gratings with any arbitrary chirp profile was proposed by Putman *et.al.* [12]. A chirp of 2nm was achieved. The technique is very flexible and easy to implement with good controllability. We have demonstrated that linearly chirped fibre gratings with up to 4.8nm chirps can be produced controllably by this technique. Such chirped gratings are ideal for use in dispersion compensation in an optical fibre link and optical pulse shaping.

A taper is first made on the outer cladding of a section of photosensitive optical fibre by differential etching along the length of the fibre. The small end of the taper usually has a diameter between 50μm to 100μm. The fibre core is not affected by the process and the fibre strength is not significantly affected. A grating is then written over the taper in the conventional manner with either zero or some applied tension on the fibre. Tension will create a strain gradient along the length of the taper because the local strain is inversely proportional to the local fibre cross-sectional area. This strain gradient is used to introduce a chirp during/after a grating is written over the taper. Any chirp profile can be accommodated by varying the taper profile. The tension on the fibre can also be used to tune the central wavelength and chirp bandwidth of the grating if desired. The final device is easy to package and is potentially insensitive to polarisation, unlike the cantilever technique [2]. The process for making the taper can be easily modified for batch production.

Theory: Two different methods can be used to write gratings over a taper. In method A, an unchirped grating is written without any tension being applied to the fibre (see fig.1). If the fibre is placed under tension after writing, a strain gradient develops along the grating. The grating is chirped as the strain gradient causes both the effective modal index and grating pitch to vary along its length. When a tension F is applied to the fibre, the local change of Bragg wavelength $\Delta\lambda_g$ at a fibre radius r will be:

$$\frac{\Delta\lambda_g}{\lambda_g} = \frac{F}{\pi E r^2} - \chi\frac{F}{\pi E r^2} \qquad (1)$$

where E is Young's modulus and $\chi = 0.22$ for silica. The first term arises from the change of grating pitch (fibre lengthening effect) and the second term from the change of refractive index due to the stress-optics effect. The stress-optic effect cancels out part of the chirp from the fibre lengthening effect since they have opposite signs.

In method B, a grating is written over the taper in the usual manner while the fibre is held under tension (see fig.1). The grating is chirped due to the refractive index gradient along the length of the taper, arising from the strain gradient. The grating pitch, however, does not vary over the taper in this case. When the tension on the fibre is removed after writing, the strain gradient disappears; this removes the chirp due to the index gradient. Another chirp is, however, developed at the same time; this is because the grating pitch is no longer uniform as a result of the removal of the strain gradient (reverse of the lengthening effect, see fig.1). The device can then be packaged strain-free. The stress-optic effect does not play any part in the final device with this method, therefore only the first term in equation 1 remains. The overall chirp is thus larger than that in method A for the same applied force.

To make a linearly chirped grating, the following relation between the taper radius and distance is required:

$$\frac{1}{r^2(z)} = \frac{1}{l}\left(\frac{1}{r^2(l)} - \frac{1}{r^2(0)}\right)z + \frac{1}{r^2(0)} \qquad (2)$$

where l is the taper length, and r(z) is the fibre radius at axial position z. Some possible profiles are given in fig. 2. A large chirp requires a strong taper, as will be discussed later. We define the total chirp as the Bragg wavelength difference at two ends of the chirped grating. For method A, the total chirp can be given as:

$$Total\ chirp = \frac{(1-\chi)F\lambda_0}{\pi E}\left(\frac{1}{r^2(l)} - \frac{1}{r^2(0)}\right) \qquad (3)$$

where λ_0 is the central wavelength of the chirped grating. To obtain the total chirp for method B after the tension is removed, simply put $\chi=0$ in equation 3. A large difference between r(0) and r(l) (strong taper) is required to achieve a large chirp for the same amount of applied force. For r(0) = 125μm, the required F and r(l) for method B to achieve certain amounts of total chirp after the tension is removed are plotted in Fig.3.

It should be pointed out that by varying the tension on the fibre, the total amount of chirp and the central reflection wavelength can be adjusted. This can be used to fine tune the device if required. Fibres can normally take several percent of strain. The force required to achieve 1% strain in a 60μm fibre is ~2N; 5nm chirp is, therefore, easily achievable.

Experiments: The tapers were made by having a fibre immersed in a HF solution contained in a beaker and moving the beaker down at a controlled rate [13] (see fig.4). The etching rate is linear with time, therefore any desired taper profile can be produced by controlling the movement the beaker. Two buffer oils were used both under (trichloroethylene) and above (decahydronaphtalene + 10% dichlorotoluene) the HF solution, therefore only the part of the fibre in contact with the HF solution was etched. This was necessary to obtain good fibre diameter control at the two ends of a taper and to protect the rest of the fibre from being etched. A very thin HF layer of several millimetres can be used to obtain any taper profile, but the spatial resolution of the taper can be limited by the HF layer thickness. Too thin a layer of HF will give a much reduced etching rate and the controllability of the taper profile may also be affected because the different liquids can mix at the interfaces and the etching products can reduce the etching rate slightly during taper fabrication in this case. Alternatively, a HF layer with a thickness larger than the intended taper can be used. In this case, a much better spatial resolution can be obtained, which is limited to $\sim 50\mu m$ by mixing at the liquid interfaces. The controllability of the taper profiles is also much improved because the etching rate is virtually unaffected by the etching products as a result of the much larger quantity of HF solution used. It can, however, only produce tapers with monotonic profiles. We used this method to make the linearly chirped gratings described later in the paper. Good controllability over the taper profiles were found [13] and batches of 6 to 8 tapers were made at the same time. Good repeatability and consistency were also found.

32% aqueous HF solution was normally used which reduced the fibre diameter at $1.07\mu m$/min at room temperature. A taper with large and small end diameter of $125\mu m$ and $60\mu m$ respectively took about 1 hour to make using this solution. Less time is obviously required if stronger HF solution or higher solution temperature is used.

A grating was then written over a taper by scanning an unfocused KrF excimer laser beam through a phase mask with no tension applied to the fibre (method A). The phase mask had a pitch of $1.06\mu m$. The KrF laser is a line-narrowed system operating at 248.5nm with a pulse width of 20ns. The pulse fluence was set at ~0.1J/cm^2 and the repetition rate was 20Hz. The masked beam width was ~3mm. The scan speed was 1.5 mm/min. The fibre had a NA of ~0.29 and a first order mode cut-off wavelength of ~1.41μm. The Bragg wavelength of the fibre grating was at 1555.3 nm when written. The grating was not chirped after writing as expected and was only chirped when tension was applied to the fibre (see fig.5). The taper profile was measured with an Anritsu fibre diameter monitor on an optical fibre pulling tower while moving the taper vertically with the preform feeder. The measured taper profile fitted well with the designed profile to give a linear chirp [13]. The diameters at the two ends of the taper in this case were 125.1μm and 66.7μm respectively. The taper length was 25mm and a ~40mm thick HF layer was used to etch the taper. The length of the grating was ~19mm, slightly less than that of the taper to ensure that the grating was entirely within the taper. The grating peak reflectivity was ~30% before tension was applied and was ~5.4% when 86g of tension was applied to give 2.1nm chirp (the central reflection wavelength shifted to 1557.8nm). Fig.5 gives the total chirp of the grating when different tensions were applied to the fibre after writing. The solid line shows the theoretical prediction from equation 3. The measured chirp fits well to what is predicted from the theory.

A second grating was written in the same way as the first grating but with 94g of tension applied to the fibre during writing (method B). The excimer pulse repetition rate was set at 40Hz and the scan speed was 3mm/min. The taper was again designed to give a linear chirp and the measured profile fitted well with the design

[13]. Diameters at two ends of the taper in this case were 125.6μm and 56.9μm respectively. The grating was about 19mm long within the 25mm long taper etched with a 40mm thick HF solution. The grating had a reflectivity of 47% and a 1.1nm chirp when written. It had a reflectivity of 14% and a 4.8nm chirp when the tension was totally removed [13]. The central reflection wavelengths when tensioned at 94g and 0g were 1554.8nm and 1552.0nm respectively. Fig.6 shows the total chirp of the grating when different tension was applied. The theoretical prediction is represented by the solid line and again fits well to the measured value.

A third grating was written in the same way as the second grating with 94g of tension applied during writing. The taper was hydrogenated at room temperature and 80 bars of pressure for 2 weeks. The excimer pulse repetition rate was set at 20Hz with a scan speed of 3mm/min. The taper profile was again designed to give a linear chirp. The diameters at two ends of the taper were 124μm and 74μm respectively. Fig.7 shows the excellent fit between the measured taper profile (dots) and the design (solid line). The grating reflectivity was nearly 100% both when written and when the tension was removed. The chirps at tensions of 94g and 0g were ~0.5nm and ~2.5nm respectively. Fig.8 gives the reflection spectra of the grating at 94g, 53.3g and 0g of tension. The transmission spectrum of the same grating at 0g of tension is shown in fig.9. The spectrum shows that the transmission is approximately 17dB down at the centre of the reflection band comparing to the out-of-band transmission, and is very close to the theoretically predicted spectrum.

Conclusions: We have demonstrated a simple and flexible technique capable of accurately producing fibre Bragg gratings with any arbitrary profiles. Linearly chirped gratings with bandwidth up to 4.8nm have been made to demonstrate the controllability of the technique. Unlike techniques which use a temperature gradient, no active control is required in the final device, although tension on the fibre can be used to tune the central reflection wavelength and chirp bandwidth of the device if required. The device is potentially polarisation insensitive, unlike the technique using bent cantilevers. This technique for making tapers can also be easily modified to accommodate mass-production. The strength of the fibre is not significantly affected by the tapering. Chirped gratings made by this technique are ideal for use in dispersion compensation of an optical fibre link and optical pulse shaping. Larger chirps are also possible with stronger taper and larger tension on the fibre. Recently, 32 nm compression tuned fibre gratings was demonstrated [14]. The same compression technique can be used instead of tension in our technique to obtain much larger chirps.

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List of symbols:

λ:Lambda, Greek

χ:chi, Greek

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Figure captions:

Fig.1 This drawing shows the two different approaches for writing gratings over a taper. In method A, an uniform grating is written with no tension applied to the fibre, and the grating is chirped when a tension is applied. In method B, a slightly chirped grating is written while a tension is applied to the fibre and is further chirped as the tension is removed.

Fig.2 Some possible profiles for achieving linearly chirped gratings. The taper length in this case is 25 mm. A large chirp needs a strong taper.

Fig.3 The tension and taper required to achieve a certain desired linear chirp with method B after the tension is removed. The fibre diameter at large taper end is fixed at 125 μm. The figures next to the curves are total chirps at 1.55 μm.

Fig.4 The set-up for etching tapers.

Fig.5 The total chirp of a grating written using method A is plotted at different tensions. The solid line gives the theoretical prediction.

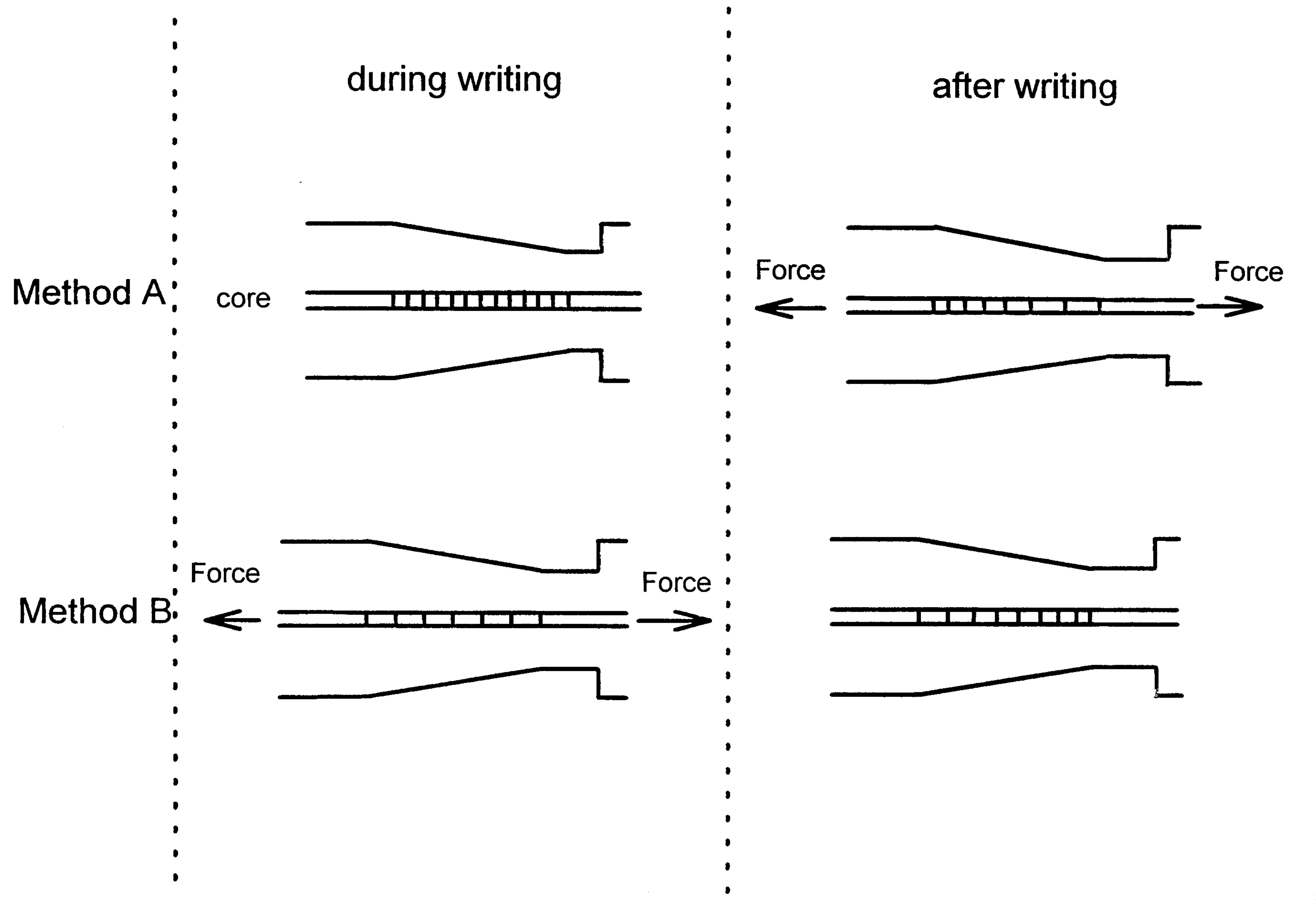
Fig.6 The total chirp of a grating written with 94 g of tension applied during writing (method B) is plotted at different subsequent tensions. The solid line gives the theoretical prediction.

Fig.7 The measured taper profile (dots) and the design (solid line) are plotted for comparison.

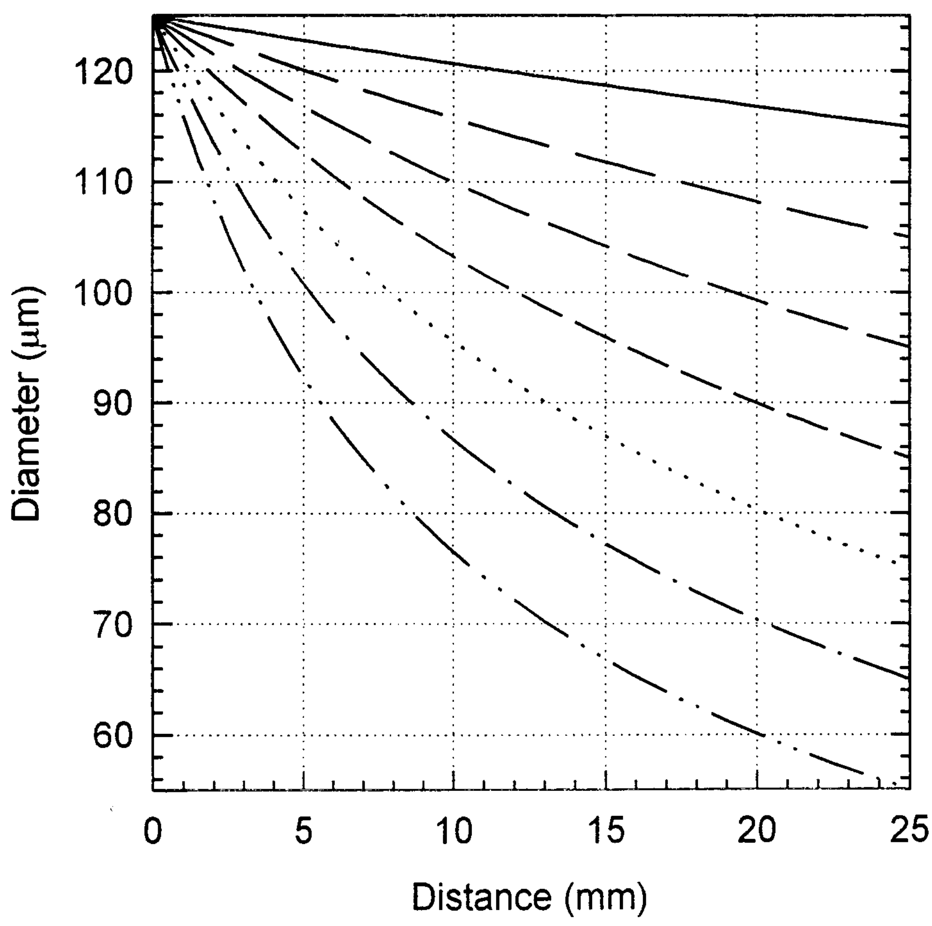
Fig.8 The reflection spectra are from a grating fabricated with 94 g of tension applied to the fibre during writing (method B). The fibre was hydrogenated. The different curves show the reflection spectra when different subsequent tensions were applied to the fibre.

Fig.9 The transmission spectrum of the grating in fig.8 when all the tension was removed.

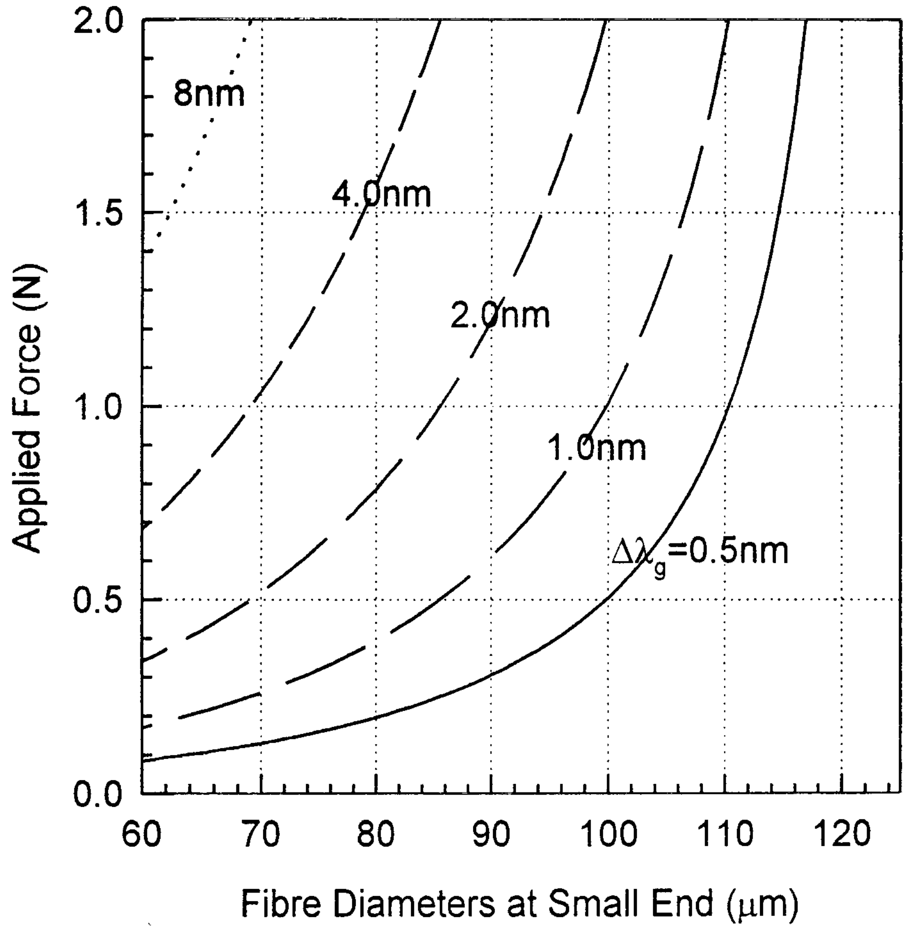
Deng et al Fig. 1



Roy et al Fig 2



Deng et al Fig.3



Dong et al

Dong et al Fig. 4

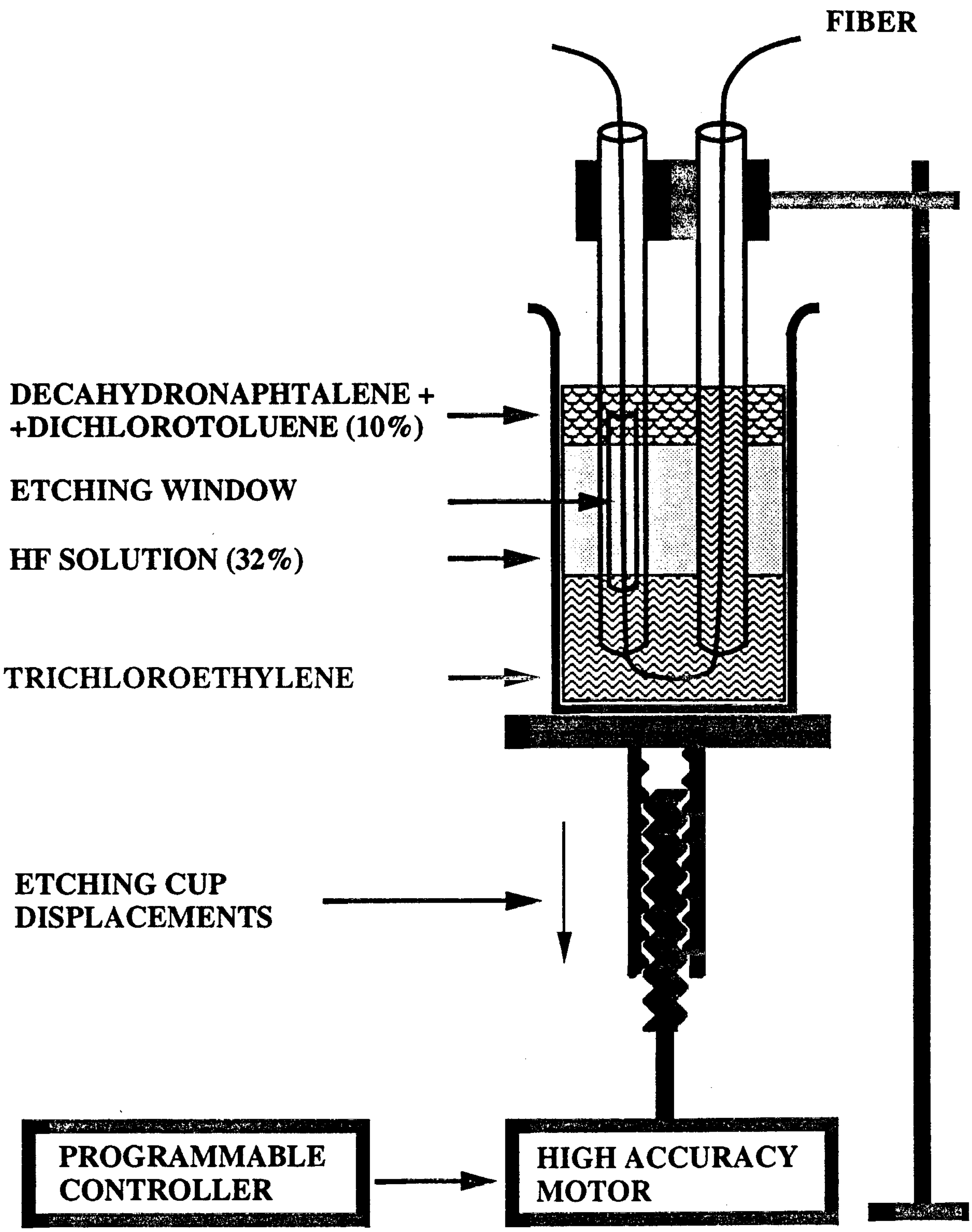
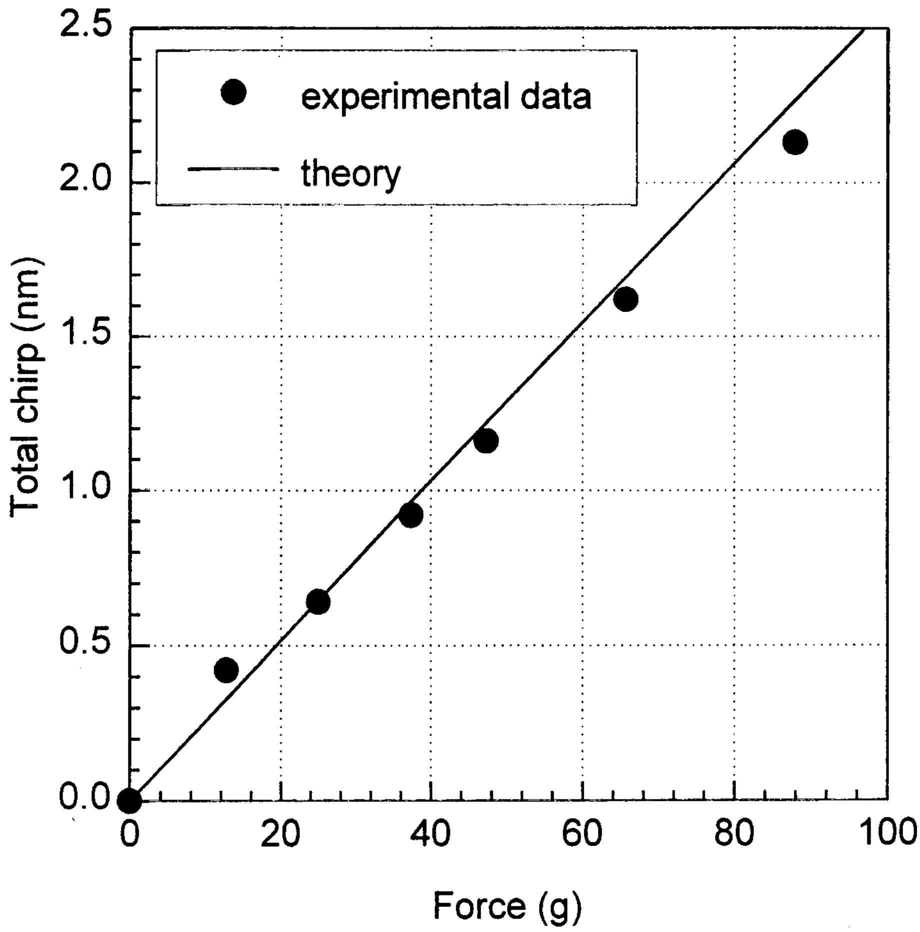
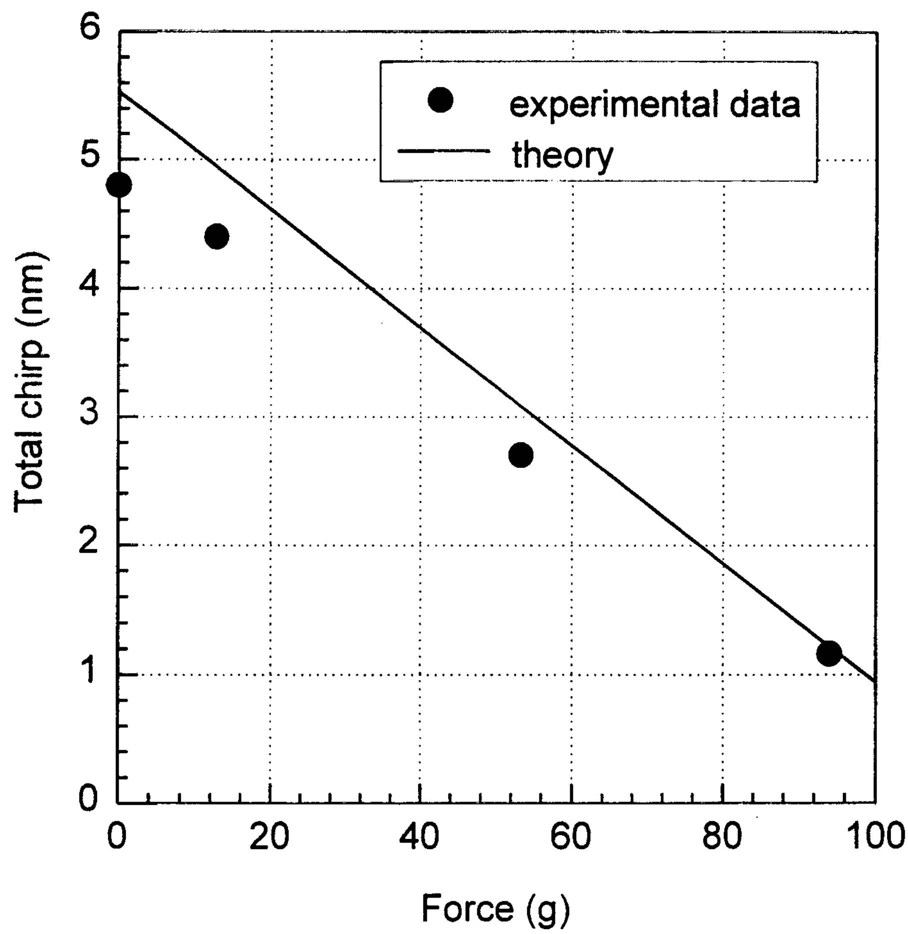


Fig. 4

Dong et al Fig 5



Dong et al Fig 6



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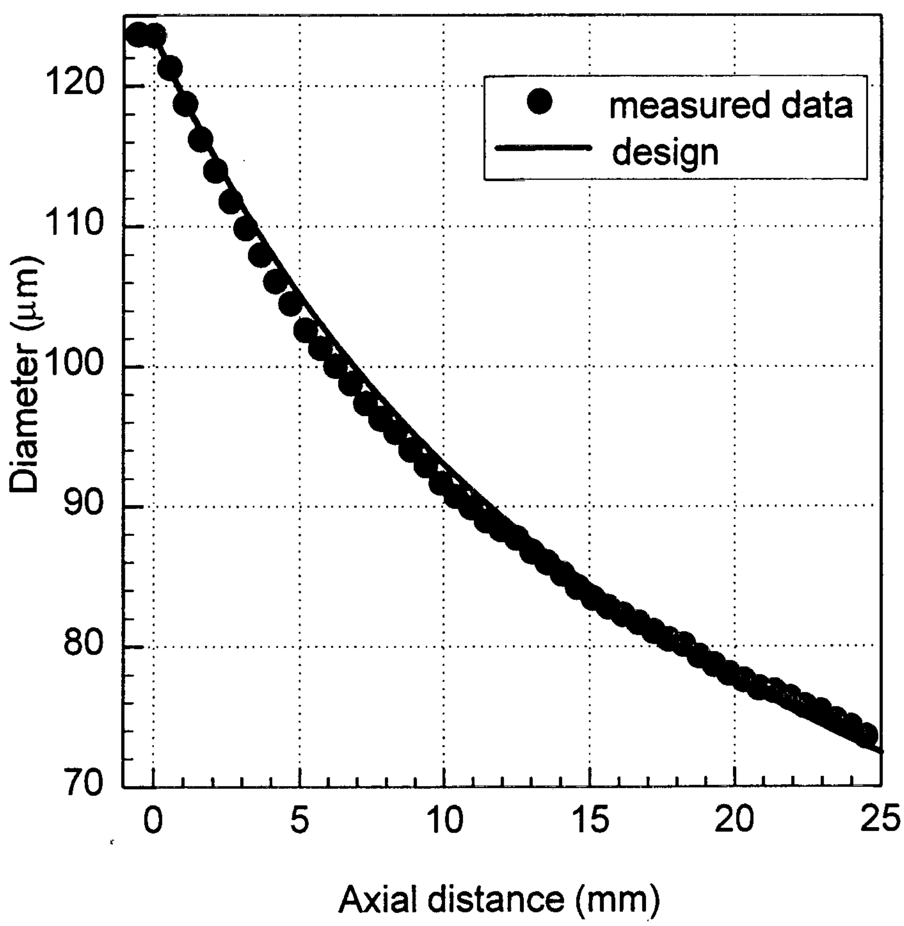
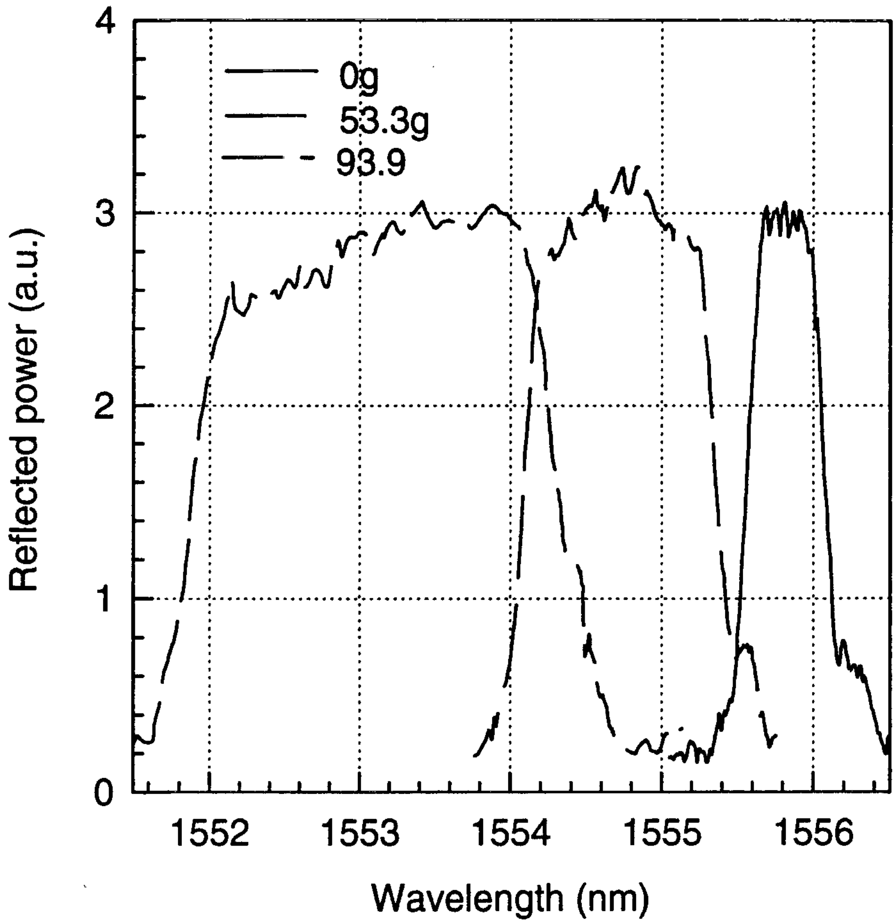


Dong et al Fig. 8



Dong et al Fig 5