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CHIRPED MOIRÉ FIBRE GRATINGS OPERATING ON TWO WAVELENGTH-CHANNELS FOR USE AS DUAL CHANNEL DISPERSION COMPENSATORS

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Abstract - Long continuously chirped Moiré fibre gratings are demonstrated. Clean, dual-channel operation with dispersion equivalent to 100 km and 200 km of standard fibre is shown from gratings of lengths 35.1 cm and 1 m. The gratings show reflection and time delay characteristics of the same high quality as previously reported in single channel chirped gratings.

Index Terms - Fibre gratings, WDM technology, dispersion compensation.

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I. Introduction

Dispersion compensation is necessary in order to allow high data rate transmission through the installed standard fibre links. Several dispersion compensation techniques exists, including dispersion compensating fibre, phase conjugation and chirped fibre gratings. Of these, chirped fibre gratings offer many advantages including compactness, low-loss and low non-linearity. Recent error-free 10 Gbit/s and 40 Gbit/s transmission experiments at 1.55 μm over 109 km of standard fibre together with the possibility of simultaneous compensation of 2nd and 3rd order dispersion confirm the potential of this solution [1,2,3].

Interest in wavelength division multiplexing (WDM) has increased markedly over recent years driven by the rapid increase in communication traffic. Different schemes have been proposed to cope with the increased density of information. One is to multiplex the data in time

(TDM), another is to wavelength multiplex data (WDM). Multi-channel chirped gratings have been demonstrated previously using sampled gratings [4]. These devices represents an interesting approach to the WDM solution but the lack of reflection equality and bandwidth together with a missing control over the exact number of wavelength channels required may limit the practicality of these. Moiré gratings and techniques to manufacture them have also been demonstrated [5,6] but none with clear distinction between the channels. The advantage of multichannel gratings is that they exhibit characteristics similar to those of several single-channel gratings but are written within a single length of fibre hence offering higher stability when packaged and potentially lower cost.

In this paper we demonstrate for the first time chirped Moiré fibre gratings operating on 2 clearly separated wavelength-channels for use as dual channel dispersion compensators in a WDM scheme. Two devices with dispersion designed to compensate for 1.5 μm transmission through either 100 km or 200 km of standard telecommunication fibre with a dispersion of 17 ps/nm/km are shown.

II. Theoretical background

According to Fourier theory a sinuosoidal variation in the refractive index of a grating with Bragg wavelength λ_B will generate two identical sidebands symmetrically around the Bragg wavelength, see Fig. 1. The separation of the two generated wavelengths is determined by the period P of the index modulation

$$\Delta\lambda = \frac{\lambda_B^2}{2 \cdot n_{eff} \cdot P} \tag{1}$$

where n_{eff} the effective refractive index in the grating. Fourier theory again predicts that a change in wavelength along the length of the grating structure will result in identical dispersion characteristics in the two generated wavelength channels. Any imperfect phaseshift between the modulation sections will disturb the coherent picture of the sinousoidal refractive index profile. This will generate sidebands of unequal strength outside the two centre sidebands and will disturb the coupling coefficient in each of these hence causing unidentical dispersions and bandwidths.

III. Fabrication technique

The gratings are made using an extented version of the scanning fibre/phase mask technique developed at the ORC [7]. This technique allows non-uniform grating formation with a uniform phase mask. An intracavity frequency doubled argon ion laser producing 100 mW of 244 nm CW light is employed as UV source. A total fluence of ~0.8 kJ/cm^2 is used to write the gratings. The gratings are written in a Deuterium loaded Ge/Si fibre with an NA ~ 0.2, and the time taken to write each grating is just 30 min. In order to smooth out the time delay ripples the gratings are apodised over 10 % of the total grating length at either end of the grating. The periodic modulation of the refractive index is obtained by sin-apodising the grating so each period of the modulation consists of a fully apodised grating and a controlled π-phaseshift.

The gratings are characterised for reflectivity and time delay with a wavelength resolution of 2 pm using a tunable laser together with a high precision wavemeter.

IV. Results and discussion

Fig. 1 shows the refractive index profile structure of the gratings. Fig. 2 a) & b) shows the reflection and time delay spectra of the two channels in a 1 m long continuously chirped Moiré grating designed to compensate 200 km dispersion in a fibre with a dispersion of 17 ps/nm/km. The Bragg wavelength of the grating is 1531.9 nm and the grating has a refractive index modulation period of 291 μm leading to a wavelength separation of the two reflection channels by 2.7 nm (338 GHz). The bandwidth of each channel is identical at ~2.7 nm. The two channels both experience a total time delay of 9672 ps where channel I has a dispersion of 3630 ps/nm and channel II a dispersion of 3607 ps/nm a value given by the length of the grating and the channel bandwidth. Plots for the deviation from linear time delay are shown in Fig. 2 c) & d). These show that there are small deviations from the perfect linear time delay expected from the gratings. These imperfections are believed to be due to environmental factors this either phase-mask errors or fibre imperfections, both of these will cause a small change in the effective index modulation a change that will show up as an extra chirp in the channels delay characteristics. Because of the Moiré structure any imperfections will show up in the delay characteristics of both channels. The grating was also tested in transmission and each dispersion channel showed a transmission loss of ~10 dB indicating a reflectivity of ~ 90 %.

Fig. 3 a) & b) shows a 35.1 cm long chirped Moiré grating designed to compensate 100 km of dispersion in standard fibre. This grating has a channel separation of 2.4 nm (300 GHz) and each channel in the grating has a bandwidth of ~ 2 nm; this yields a dispersion of ~1770 ps/nm for each channel. In this case the strength of the channels is ~8 dB (~84 %).

From figures 2 and 3 we can see that the two channels are nearly identical in terms of reflectivity and time delay. In both gratings channel I is the weaker, this is due to cladding-mode loss generated by channel II. We have recently proposed an apodisation technique [8] to remove this effect that in a real system is unacceptable.

Because these devices rely on very accurate phase control along the grating any phase imperfections will show up on the reflection and time-delay characteristics of the gratings to a larger extent than similar imperfections would in a single channel chirped grating. A scan of wavelengths well out of band of these gratings show no evidence of additional sidebands other than the two produced by the superstructure. This shows that control of the phase along the length of the grating is maintained despite the complex combination of full apodisation and phase-shifts within ~ 0.3 mm. These results demonstrate full control of the grating parameters available from today's technology.

One advantage of these "non-uniform" chirped fibre Bragg gratings is that the characteristics of several reflection wavelength gratings can be written into the same piece of fibre in one step, and therefore expensive problems such as implementation of several gratings either in series or on different ports of a circulator are avoided. Our results also show that chirped Moiré fibre gratings offer a robust way of achieving equal dispersion characteristics on two and only two channels. In addition they show that the use of chirped Moiré fibre gratings greatly simplifies the dispersion and wavelength matching of gratings where very accurate wavelength separations are required for implementation in the same WDM link.

V. Conclusion

We have demonstrated long continouosly chirped Moiré fibre gratings with equal strength and linear dispersion characteristics in two channels designed to compensate the dispersion of 100 km and 200 km of standard telecommunication fibre. The gratings are up to 1 m long and are written using a recently developed continuous writing technique. These types of gratings could find important applications in WDM systems.

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References

[1] COLE, M. J., GEIGER, H., LAMING, R. I., ZERVAS, M. N., LOH, W. H. and

GUSMEROLI, V.: 'Broadband Dispersion-Compensating Chirped Fibre Bragg Gratings in a 10 Gbit/s NRZ 110km Standard Step Index Monomode Fibre Link' , *Electron. Lett.*, 1997, **33**, (1), pp.70-71.

[2] DONG, L., COLE, M. J., ELLIS, A. D., DURKIN, M., IBSEN, M., GUSMEROLI, V. and LAMING, R. I: '40 Gbit/s 1.55 μm transmission over 109 km of non-dispersion shifted fibre with long continuously chirped fibre gratings', in proceedings to *OFC'97*, PD6, San Jose, USA, 1997.

[3] IBSEN, M., DURKIN, M. K., ENNSER, K., COLE, M. J., and LAMING, R. I., 'Long continuously chirped fibre Bragg gratings for compensation of linear- and 3rd order-dispersion', Accepted for publication on *ECOC'97,* Edinburgh, UK, 22-25 September 1997.

[4] OUELLETTE, F., KRUG, P. A., STEPHENS, T., DHOSI, G. and EGGLETON B.: 'Broadband and WDM dispersion compensation using chirped sampled fibre Bragg gratings', *Electron. Lett.*, 1995, **31**, (11), pp.899-901.

[5] REID, D. C., RAGDALE, C. M., BENNION, I., ROBBINS, D. J., BUUS, J. and STEWART W. J.: 'Phase-shifted Moiré grating fibre resonators', *Electron. Lett.*, 1990, **26**, (1), pp.10-12.

[6] LEGOUBIN, S., FERTEIN, E., DOUAY, M., BERNAGE, P., NIAY, P., BAYON, F. and GEORGES, T.: 'Formation of Moiré-grating in core of germanosilicate fibre by transverse holographic double exposure method', *Electron. Lett.*, 1991, **27**, (21), pp.1945-1947.

[7] COLE, M. J., LOH, W. H., LAMING, R. I., ZERVAS, M. N. and BARCELOS, S.: 'Moving fibre/phase-mask scanning beam technique for enhanced flexibility in producing fibre gratings with a uniform phase-mask', *Electron. Lett.*, 1995, **31**, (17), pp. 1488-1489.

[8] DURKIN, M. K., IBSEN, M., GUSMEROLI, V. and LAMING, R. I.: 'Equalisation of spectral non-uniformities in broad-band chirped fibre gratings', Accepted for publication on *Conf. on Bragg Gratings, Photosensitivity, and Poling in Glass Fibers and Waveguides: Applications and Fundamentals*, Williamsburg, Virginia, USA, October 26-28, 1997.

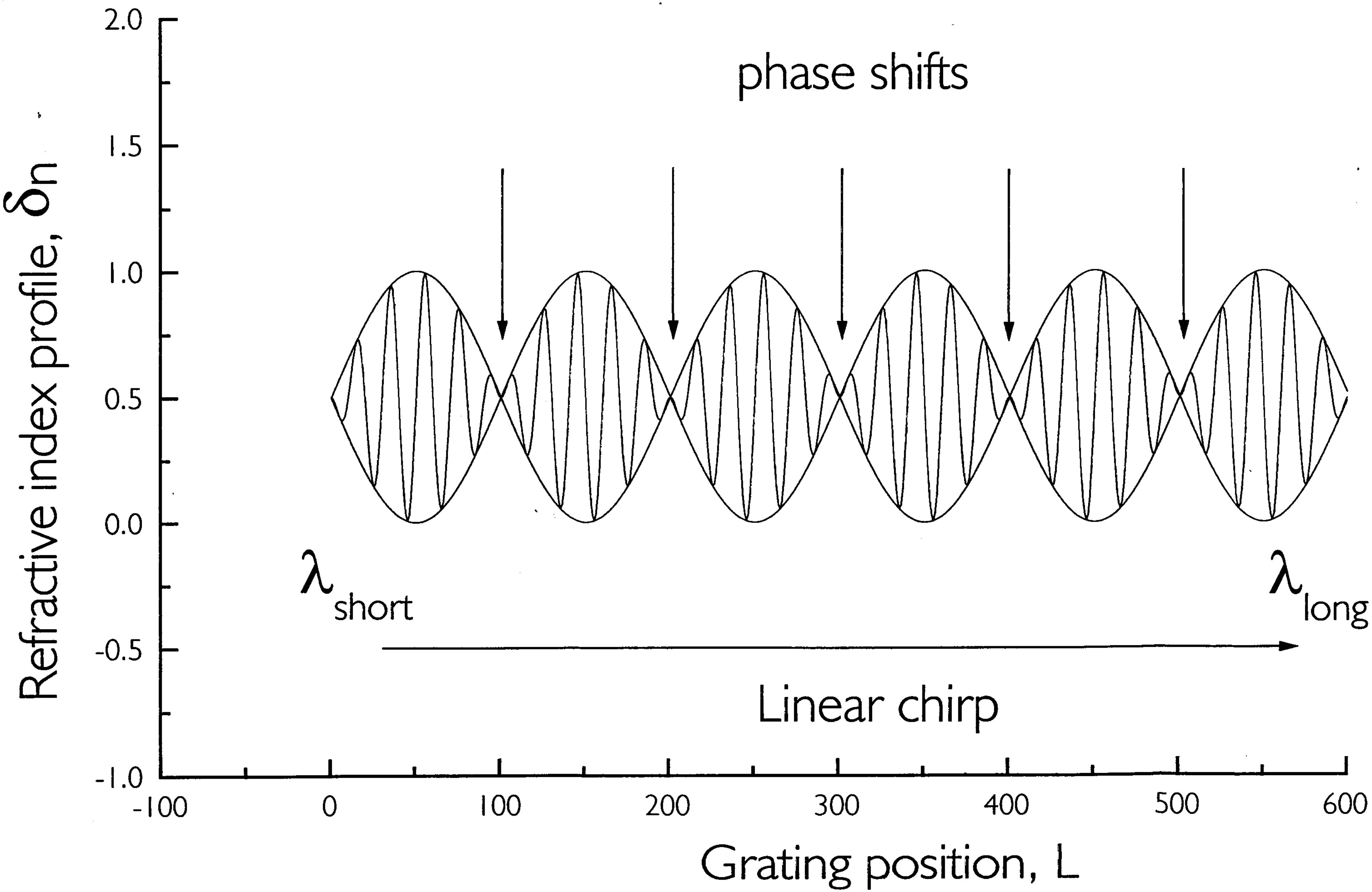
FIGURE CAPTIONS.

Figure 1 *Refractive index-profile of the chirped Moiré fibre gratings.*

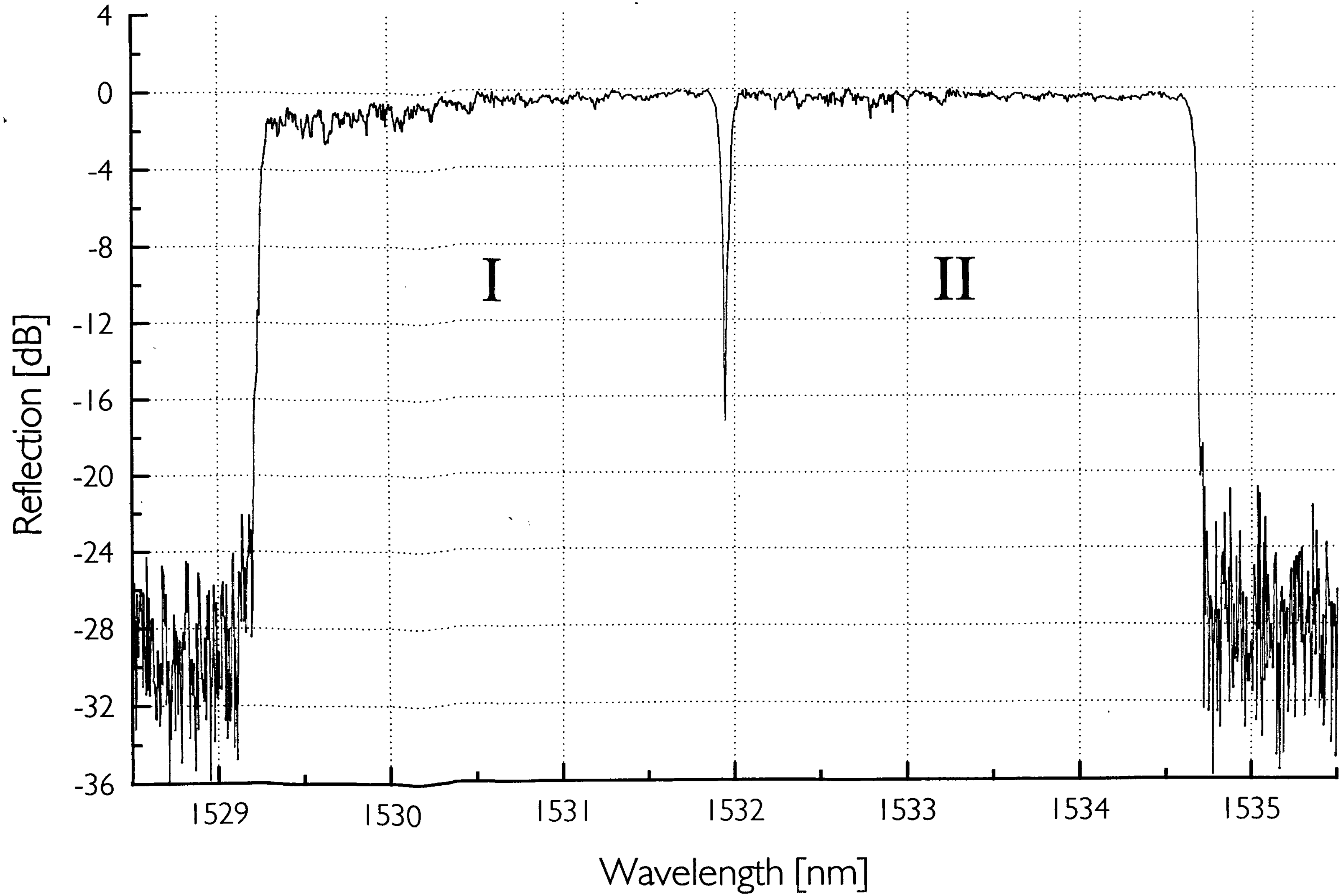
Figure 2 *a) & b) Reflection and time delay characteristics of a 1 m long chirped Moiré grating with a channel bandwidth of 2.7 nm (338 GHz) and a channel separation of 2.7 nm. The dispersion in the channels is D_I=-3630 ps/nm and D_{II}=-3607 ps/nm.*

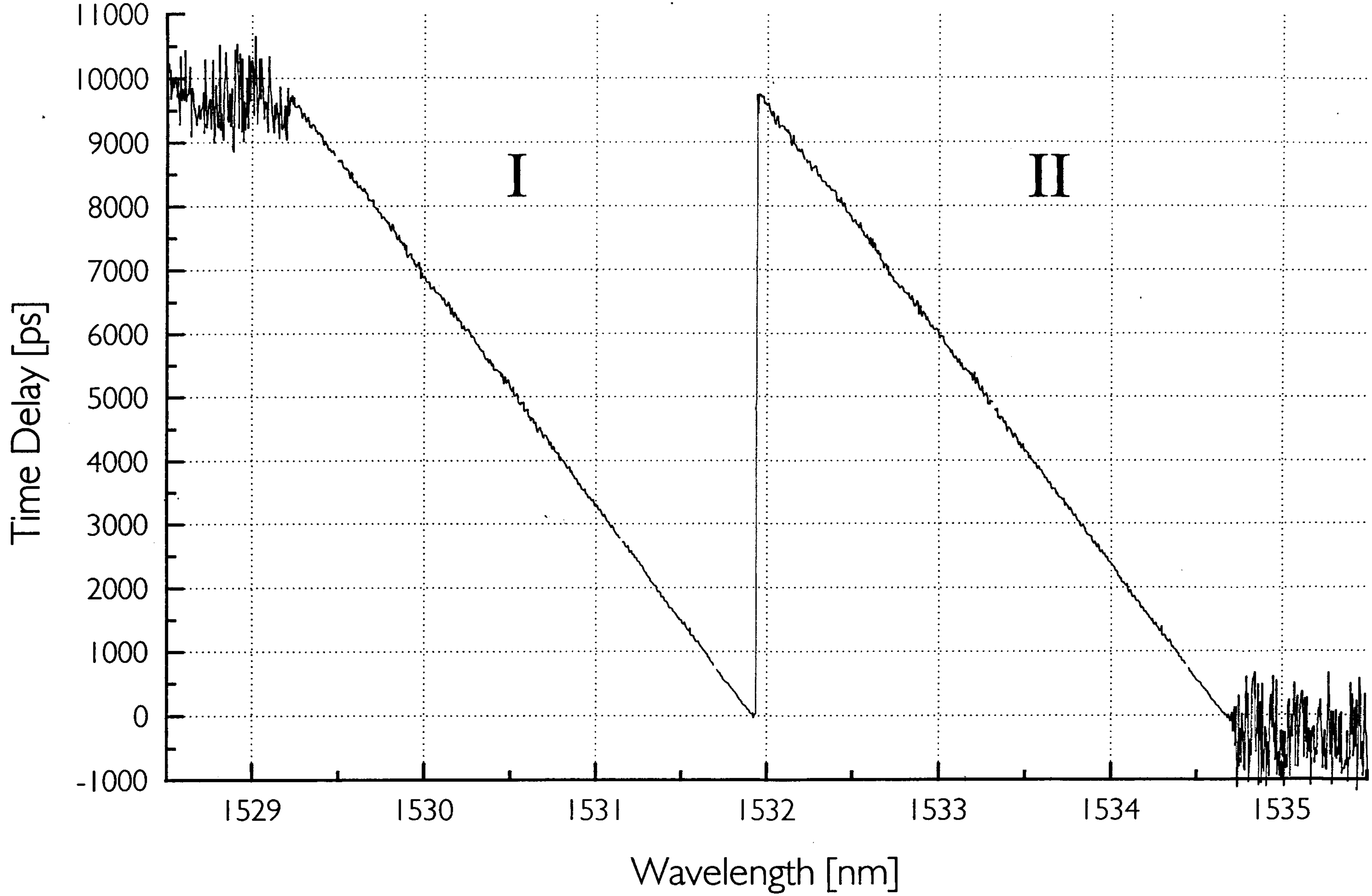
c) & d) Deviations from linear time delay in channel I and II.

Figure 3 *a) & b) Reflection and time delay characteristics of a 35.1 cm long chirped Moiré grating with a channel bandwidth of 2.0 nm (250 GHz) and a channel separation of 300 GHz. The dispersion in the channels is D_I=-1772 ps/nm and D_{II}=-1768 ps/nm.*



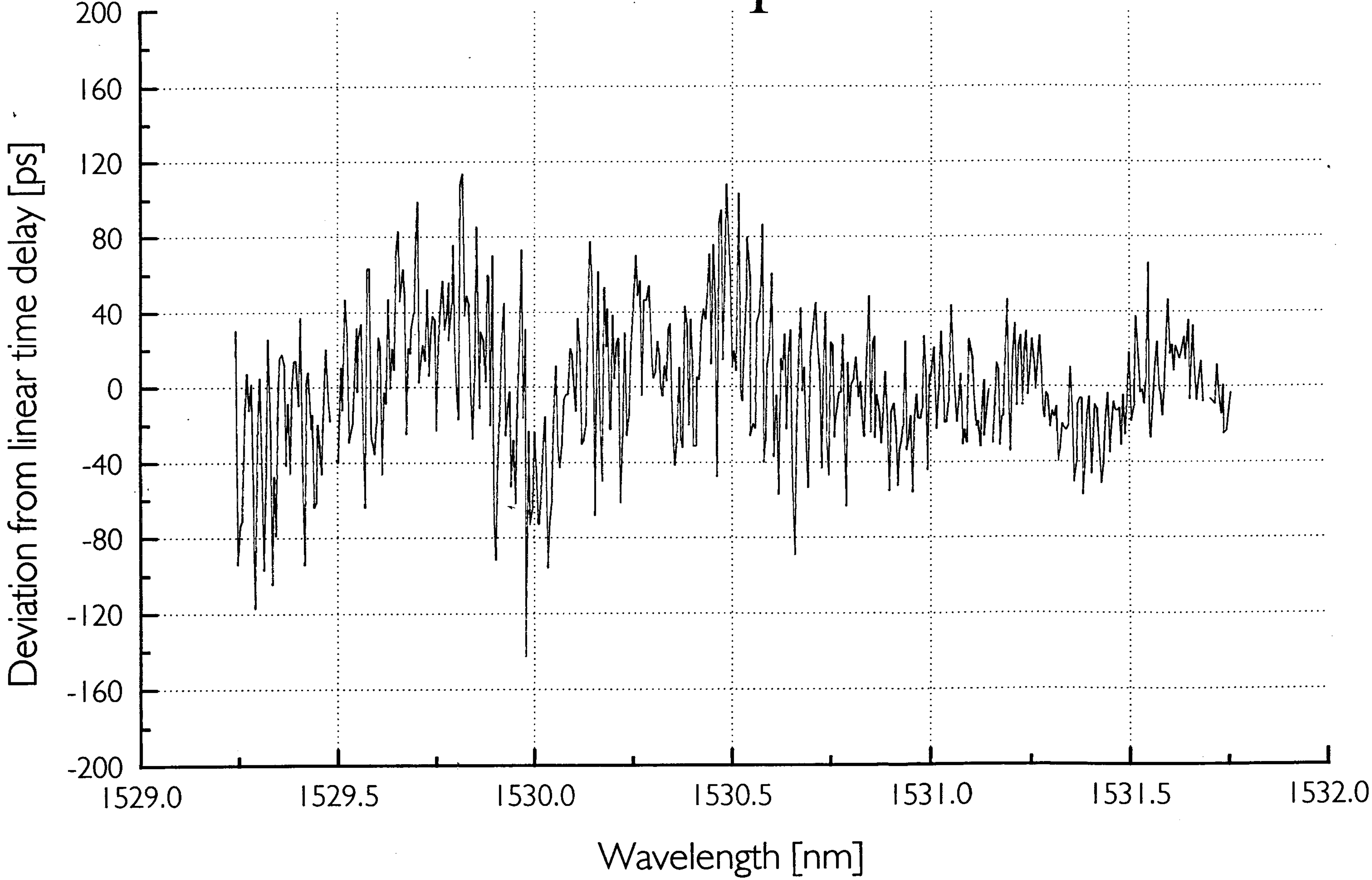
Refractive index profile, δn
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
phase shifts
λshort
λlong
Linear chirp
-100
0
100
200
300
400
500
600
Grating position, L


4
0
-4
-8
-12
-16
-20
-24
-28
-32
-36
Reflection [dB]
I
II
1529
1530
1531
1532
1533
1534
1535
Wavelength [nm]

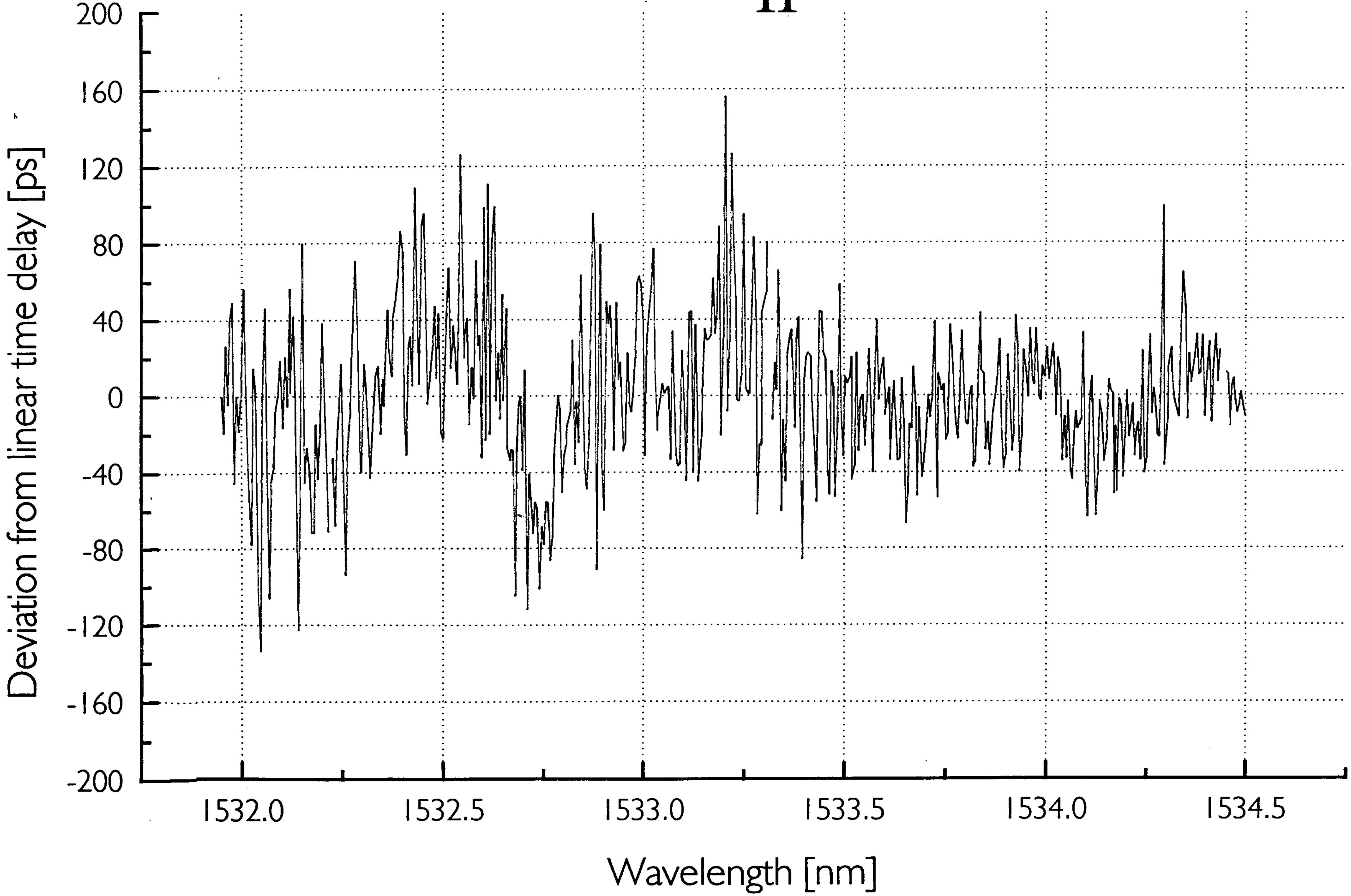


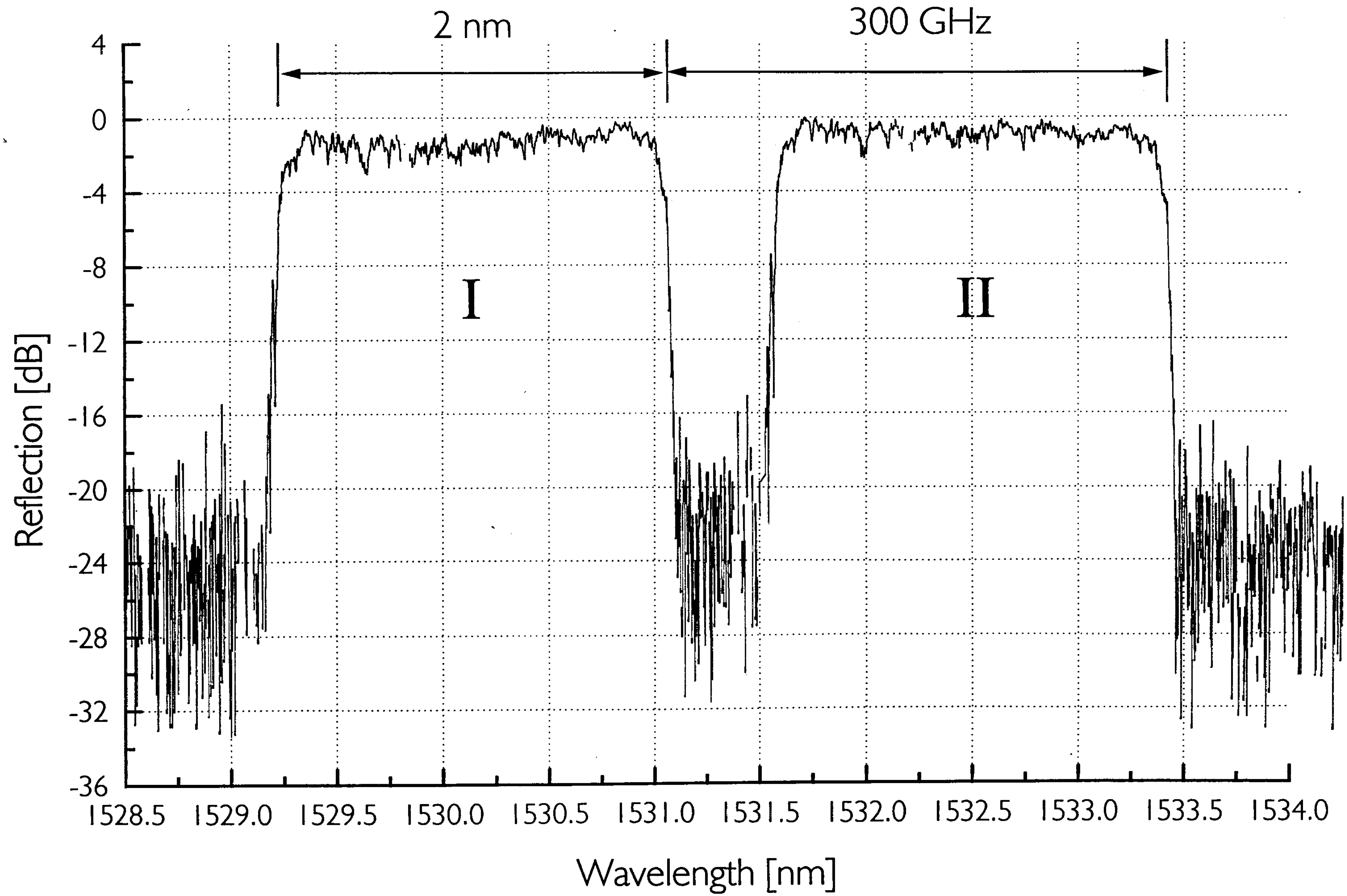
Time Delay [ps]
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
I
II
1529
1530
1531
1532
1533
1534
1535
Wavelength [nm]

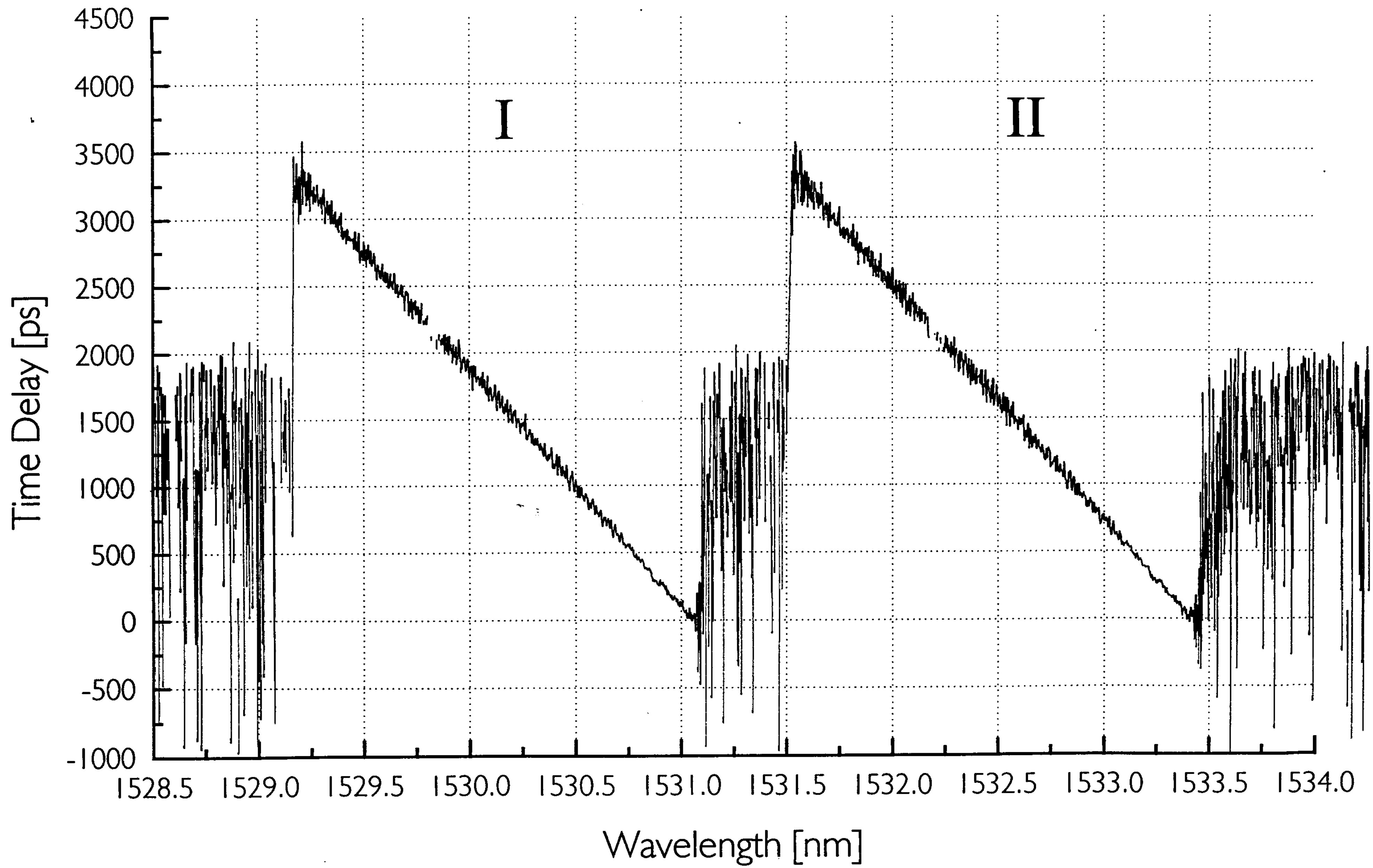
I


200
160
120
80
40
0
-40
-80
-120
-160
-200
Deviation from linear time delay [ps]
1529.0
1529.5
1530.0
1530.5
1531.0
1531.5
1532.0
Wavelength [nm]

II


200
160
120
80
40
0
-40
-80
-120
-160
-200
Deviation from linear time delay [ps]
1532.0
1532.5
1533.0
1533.5
1534.0
1534.5
Wavelength [nm]


2 nm
300 GHz
I
II
Reflection [dB]
4
0
-4
-8
-12
-16
-20
-24
-28
-32
-36
1528.5
1529.0
1529.5
1530.0
1530.5
1531.0
1531.5
1532.0
1532.5
1533.0
1533.5
1534.0
Wavelength [nm]


I
II
Time Delay [ps]
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
1528.5
1529.0
1529.5
1530.0
1530.5
1531.0
1531.5
1532.0
1532.5
1533.0
1533.5
1534.0
Wavelength [nm]