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A STUDY OF FIBRE BRAGG GRATINGS WITH VARIOUS CHIRP PROFILES MADE IN ETCHED TAPERS

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Abstract.

We have studied, both theoretically and experimentally, fibre Bragg gratings with a number of different chirp profiles. These chirp profiles can be easily achieved with a recently demonstrated technique involving a taper of desired profile being etched into the cladding of a fibre. Performances of gratings with linear, quadratic, periodically modulated and step chirp profiles are numerically analysed. The versatility of the technique is demonstrated when linearly and quadratically chirped gratings were made as examples of continuous chirp and gratings with step chirps were made as examples of discontinuously chirped structure.

INTRODUCTION:

Chirped Bragg gratings are playing an important role in modern optical fibre technology due to the large number of applications in key fields such as dispersion compensation, wavelength division multiplexing, pulse shaping, filters, DFB lasers and sensors. Several chirping techniques have been developed in the last few years. A chirp can be introduce in a grating by using a temperature gradient [1], strain gradient [2, 3, 4, 5], a refractive index gradient [6, 7] or variation of the period of the grating [8, 9, 10, 11, 12].

The merits of these techniques lie in three main areas: the possibility of using a phase mask or an interferometric set-up, the capability to produce different chirp profiles in a controlled manner and the possibility of tuning the chirped grating.

The techniques based on temperature gradients [1] present a poor controllability and versatility in achieving a desired chirp profile. The techniques based on effective refractive index gradients by tapering the fibre core [6] or by using a second exposure [7] have the same problem. Techniques based on moving the fibre with respect to the phase mask [9] offer excellent controllability but the operation wavelength is constrained by the phase mask period. It is difficult to modify the total chirp of the grating once it has been fabricated and it is also difficult to achieve large chirps. Tilting the fibre respect to the phase mask [8] or using a chirped phase mask [10] present the same problem. Chirped gratings can be written in a curved fibre [12] with either an interferometer or a phase mask, the chirp profile can be controlled by the fibre curvature. Zhang *et al.* [13] have recently demonstrated good quality gratings with linear and non-linear chirp profiles by using this technique. Only continuous variations of the Bragg wavelength can be achieved with this technique and it is difficult to modify the chirp of the gratings after they have been fabricated. This technique also requires a laser with good uniformity in the direction perpendicular to the fibre and it can be polarisation sensitive.

The chirping techniques based on a strain gradient along the fibre offer good controllability. Linearly chirped gratings have been demonstrated by modifying the tension in the fibre while scanning the writing laser beam [2] or by using a tapered cantilever [5]. The total chirp can be controlled by the force applied to the cantilever in the second technique.

Either a phase mask or an interferometer can be used with these techniques and they are potentially able to produce different chirp profiles although this has not been reported yet.

Two independent groups have demonstrated a new chirping technique based on a cladding tapered fibre [4, 14]. Since the fibre has a non-uniform diameter, an applied tension results in a strain gradient and, consequently, in a non-uniform Bragg wavelength along the grating. The tapers in the cladding of the fibres are made by withdrawing a fibre immersed in a HF solution at a controlled speed and the grating can be written in the fibre before or after the taper is etched. There are two ways to write the grating: a) an uniform grating is written in a tension-free fibre, a chirp appears when the fibre is subjected to some tension. b) a grating is written in a fibre under tension (this is a chirped grating because the photoelastic effect changes the refractive index along the fibre), a strong chirp can be made when the tension is relaxed. The total chirp in the second case is larger than in the first one when using the same tension. All fabrication details are discussed in reference [14]. The gratings can be written by an interferometer or by a phase mask, the chirp can be tuned by the tension applied to the fibre. As we will demonstrate in this paper, various continuous and discontinuous chirp profiles can be produced because the etching process can be accurately controlled.

In this paper we present a theoretical and experimental analysis of Bragg gratings fabricated in etched fibres to produce different kinds of chirp profiles. Tapers to produce linear and quadratic variation of the Bragg wavelength have been analysed and their phase and amplitude response calculated for different applied tensions. Gratings in fibres with a square corrugation in cladding diameter have been also studied, this corrugation produces a periodic modulation of the Bragg wavelength along the grating (phase modulated gratings) that splits the reflection band of the original grating into several bands. The last structure we analysed is a grating in a fibre with a step in the cladding, the step gives rise to two consecutive gratings with different Bragg wavelengths (phase mismatched gratings), a transmission band in centre of the reflection band can be obtained with this configuration, it is demonstrated that two tapers at both sides of the step can increase the free spectrum bandwidth of the bandpass filter.

Three batches of fibres were etched to produce linear, quadratic and phase mismatched gratings. Measurements of the phase response in the linear grating show a the linear variation of the time delay with wavelength. The amplitude response of the quadratic grating has a non-uniform reflectivity in the rejection band as expected from the theoretical simulation. Amplitude measurements of the grating with a step on the middle and two tapers at both sides of the step show a transmission band between two broadened reflection bands.

THEORY.

Consider an uniform grating in an optical fibre of radius 'r', if the fibre is subjected to a tension 'F', both the grating pitch 'Λ' and the effective refractive index 'n' change and this causes a change in the Bragg wavelength λ_B given by:

$$\frac{\Delta\lambda_B}{\lambda_B} = \frac{F}{\pi E r^2} - x\frac{F}{\pi E r^2} \tag{1}$$

where E is the young's modulus and χ=0.22 for silica. The first term describes the fibre lengthening effect and the second the photoelastic effect.

It follows from equation (1) that if the grating is written in a fibre with non-uniform diameter, different parts of the grating will have different Bragg wavelength. By a proper design of the fibre diameter along the grating it is possible to produce gratings with any arbitrary chirp. The chirp function f(z/L) and the fibre profile r(z) are related by:

$$r(z) = \frac{r(0)r(L)}{\sqrt{(r(0)^2 - r(L)^2)f(z/L) + r(L)^2}} \tag{2}$$

where 'L' is the grating length. For example f(z/L) = z/L produces a linear chirp $\lambda_B(z/L) = \lambda_B(0) + \Delta\lambda_B z/L$, where $\Delta\lambda_B$ is the total chirp of the grating. $f(z/L) = (z/L)^2$ produces a quadratic chirp $\lambda_B(z/L) = \lambda_B(0) + \Delta\lambda_B(z/L)^2$ etc. A step in the fibre diameter gives rise to a discontinuity in the Bragg wavelength. These profiles are represented in figure 1.

To simulate the response of Bragg gratings two methods are usually employed in the literature, the coupled wave method and the scattering matrix method [15]. The scattering matrix method can be applied to distributed networks (such as tapered waveguides or chirp gratings) by dividing the network in short segments [16] and we used this method for our analysis.

Consider an arbitrary grating in a single mode fibre divided in 'N' short sections in which the grating is assumed to be uniform. Each section is a two-port network characterised by the length L_i, the index n_i, the period Λ_i and the coupling coefficient κ_i, and it is described by a transmission matrix $T^{(i)}$ defined as:

$$\begin{pmatrix} b_i^{(2)} \\ a_i^{(2)} \end{pmatrix} = \begin{pmatrix} T_{11}^i & T_{12}^i \\ T_{21}^i & T_{22}^i \end{pmatrix} \begin{pmatrix} a_i^{(1)} \\ b_i^{(1)} \end{pmatrix} \tag{3}$$

where $a_i^{(1)}$ and $b_i^{(1)}$ are the input and output signals at port '1' of section 'i' and $a_i^{(2)}$ and $b_i^{(2)}$ are the input and output signals at port '2' of section 'i'.

The transmission matrix of the whole system can be calculated by multiplying the transmission matrix of the single sections:

$$T = \prod_{i=1}^{N} T^{(i)} \tag{4}$$

The transmission matrix of each section can be calculated from the scattering matrix $S^{(i)}$ as:

$$\begin{aligned} T_{11}^i &= S_{21}^i - S_{22}^i S_{11}^i / S_{12}^i \\ T_{12}^i &= S_{22}^i / S_{12}^i \\ T_{21}^i &= -S_{11}^i / S_{12}^i \\ T_{22}^i &= 1 / S_{12}^i \end{aligned} \tag{5}$$

where $S^{(i)}$ is defined by:

$$\begin{pmatrix} b_i^{(1)} \\ b_i^{(2)} \end{pmatrix} = \begin{pmatrix} S_{11}^i & S_{12}^i \\ S_{21}^i & S_{22}^i \end{pmatrix} \begin{pmatrix} a_i^{(1)} \\ a_i^{(2)} \end{pmatrix} \tag{6}$$

and the scattering matrix of each uniform grating section is obtained straightforwardly from the reflected and transmitted waves of a uniform grating since the elements S_{kk} are the reflection coefficient at port 'k' and S_{kl} are the transmitted signals between ports 'k' and 'l':

$$S_{11} = S_{22} = \kappa \frac{e^{-\mu L} - e^{+\mu L}}{(\mu - j\Delta\beta)e^{-\mu L} + (\mu + j\Delta\beta)e^{+\mu L}}$$
$$S_{12} = S_{21} = \frac{2\mu}{(\mu - j\Delta\beta)e^{-\mu L} + (\mu + j\Delta\beta)e^{+\mu L}} \quad (7)$$

where $\mu^2=|\kappa|^2-\Delta\beta^2$, $\Delta\beta=\beta-\pi/\Lambda$, $\kappa=j\pi\Delta n/\lambda_B$, $\lambda_B = 2n\Lambda$ and Δn is the index modulation.

The structures depicted in figure 1 are analysed by dividing them into 50 equal-length sections (only eight sections in the phase modulated grating, curve 'c'), the difference of the grating period between two adjacent sections is small enough to assure the accuracy of the calculation. No apodization has been considered in this simulation, the main effect of the apodization will be to smooth out the ripples in the grating response. It has been assumed that the fractional shift of the Bragg wavelength in a silica fibre is 7.74 10^{-7} μstrain^{-1} , this means that a strain of 1% shifts 12nm a grating with λ_B =1550nm [17].

1) Linearly chirped grating.

Linearly chirped gratings with applications in dispersion compensation and pulse shaping [18, 19] can be fabricated by using the tapered fibre shown in figure 1 (curve 'a'). A uniform grating of $|\kappa|L=8$ is written in the taper. The reflection band of the grating shifts to longer wavelength when some tension is applied (see figure 2), at the same time the grating chirps because the Bragg wavelength changes faster in the narrow part of the taper, the peak reflectivity decreases and strong ripples appear. For easier understanding of the normalised units consider the following example: if the initial grating have a λ_B =1550, L=25mm, n=1.458 and $\Delta n=1.58\times10^{-4}$, curve 'd' would correspond to λ_B = 1550.96nm at the beginning of the taper and 1553.84nm at the end.

The time delay ($\tau = -d\Phi/d\omega$) of the reflected light looking from the large end of the taper is plotted in figure 3. The time delay has been normalised to the transit time of the light in a length of fibre twice the length of the grating $\tau_0=2nL/c$. We can see that the time delay increases linearly with the detuning because different wavelengths are reflected at different points of the grating. Short wavelength is reflected at the large end of the taper and the time delay oscillates around zero at the edge of the band, while long wavelength is reflected from the small end and the time delay oscillates around the value τ_0 at the other edge of the band.

The average slope of the curves is almost linear within the main reflection band and can be adjusted by the applied tension. As an example, curve 'd' would have a slope of 84.4ps/nm with a maximum time delay difference of 0.243ns in the wavelength interval [1550.96nm, 1553.84nm] for n=1.458 and L=25mm.

2)Quadratic chirped gratings.

Non-linear gratings have potential applications in high order dispersion compensation and non-uniform filtering [20, 21]. Consider as an example the quadratic taper of figure 1 (curve 'b'). The reflectivity of this grating is not uniform along the reflection band as it is shown in figure 4. It has the characteristic of an uniform grating at the short wavelengths and the reflectivity decreases significantly towards longer wavelengths. This is because the grating is almost uniform at the large end of the taper and has a strong chirp at the small end.

Unlike the reflection, the phase response of the quadratic gratings bears some similarity to that of the linear gratings (see figure 5). The main features are a small step in the time delay at the shorter wavelength end and a non-linear component within the reflection band. The small step is originated in the slow variation of the Bragg wavelength at the large end of the taper, the grating at this end of the taper behaves like an uniform grating.

3) Gratings with discontinuous chirps.

If the Bragg wavelength of a grating has a discontinuity comparable to the grating bandwidth, the reflection peak of the grating splits into several peaks. This type of gratings may have applications in WDM and DFB lasers [22, 23].

3.1) Phase modulated gratings.

Consider a grating in a corrugated fibre as illustrated in figure 1 (curve 'c'), this grating has a periodic repetition of two different Bragg wavelengths and can reflect multiple wavelengths as shown in figure 6. This grating behaves like a Fabry-Perot with multiple cavity lengths defined by the distance between alternate segments.

We must point out that these phase modulated gratings have a very similar response to the sampled gratings presented in [24], but they are based on different principles, sampled gratings operate by amplitude modulation of the coupling coefficient while phase modulated gratings operate by modulation of the Bragg wavelength.

3.2) Phase mismatched gratings.

This gratings are formed by two consecutive gratings with different λ_B, both gratings can be linearly chirped gratings in order to increase their bandwidth (see taper profile in figure 1, curve 'd'). When some tension is applied to this structure a transmission band appears on the middle of the reflection band, it is possible to vary the bandwidth and the reflectivity of the transmission band and reflection bands by adjusting the tension.

Notice that the phase mismatched gratings behave like phase shifted gratings [16, 22] but they have completely different configurations. Phase shifted gratings are two identical gratings with a phase delay between them, they are fabricated by introducing a phase change in an uniform grating [25] or by using a phase shifted phase mask [26].

EXPERIMENTS.

To test the ideas developed above three tapers were made by etching fibres in a HF solution (see fabrication details in reference [14]). The tapers where designed to produce linearly chirped, quadratically chirped and a phase mismatched gratings. All the tapers where made in fibres of 125μm nominal diameter and are 25 mm long, the diameters of the small end of the tapers are 73.5, 56.8 and 50.3μm respectively. The taper profiles were measured by using an Anritsu Fibre Diameter Monitor on a fibre pulling tower with an error of ±0.5μm. The taper profiles are plotted in figure 8. Gratings were written by scanning a KrF excimer laser through a phase mask.

A grating 19 mm long was written in the taper for linear chirp (fig. 8 curve 'a'), the grating length was shorter than the taper to ensure a good overlap. A load of 53.3gr was applied during grating writing, the measured phase and amplitude response of this grating when the load was relaxed are plotted in figure 9. Measurements were performed from the wide end of the taper. The time delay was obtained from the phase response measured by a Michelson interferometer while scanning in wavelength as presented in [27].

We can see that the time delay has a good linearity within the bandwidth of the grating. Time delay at both sides of the main reflection band is not resolved because of the small reflected signal. The curve has negative slope because the grating has longer Bragg wavelength at the large end than at small end of the taper when it is written under tension. The measured dispersion is 170ps/nm, the total time delay variation is 170±10ps and agrees with the 186ps calculated from the grating length (19mm) and the fibre index (1.470).

The second grating was written in the taper for quadratic chirp (figure 8, curve 'b'), the grating was 25mm long. Its amplitude response under different loads is plotted in figure 10. Note that, under small tension, the reflection peak conserves its initial shape at short wavelength and broadens at long wavelength. Under heavier loads we can see the characteristic of a slightly chirped grating at the shorter wavelength end of the reflection band, the reflectivity decreases towards longer wavelength since the narrow end of the taper produces a strong chirp.

A third grating of 19mm long was written in the taper for phase mismatched grating (figure 8, curve 'c'). We wrote a strong grating with 1.3nm bandwidth to keep the reflectivity of the two linearly chirped gratings as close as possible to 100% when the fibre is under tension. The transmission for different tensions is plotted in figure 11. When the fibre is under tension, a transmission band appears inside the reflection band, and at the same time the reflection band broadens up to 4nm because of the two gratings have been linearly chirped. The transmitted band has a transmission of ~60%. The two reflected bands are asymmetrical because the step of the taper may be displaced from the centre of the grating.

CONCLUSIONS.

We have carried out a theoretical and experimental study of Bragg gratings in optical fibres with etched non-uniform cladding diameter. The technique for using differential etching of silica fibres is capable of producing a large variety of taper profiles with applications in different fields of optic fibres. In all these gratings, the chirp can be adjusted by tension.

Linearly and quadratically chirped gratings have been fabricated, time delay measurements of the linear grating show a good linear dependence on wavelength. Transmission measurements of the quadratic taper show a non-uniform reflectivity in agreement with the theoretical prediction. Phase mismatched gratings have also been fabricated and a transmission band of 60% in the middle of a 4nm reflection band can be achieved. Phase modulated gratings have been theoretically studied, this gratings can reflect multiple bands alike sampled gratings and have potential applications in WDM.

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FIGURE CAPTIONS.

Fig.1 Tapers for different chirp profiles.

Curves: (a) linear chirp.

(b) quadratic chirp.

(c) phase modulated grating.

(d) phase mismatched grating.

Fig.2 Reflectivity of a linearly chirped grating as a function of the normalised detuning $\Delta\beta L = -(\beta-\pi/\Lambda)$ for different strains in the 125μm fibre. Normalised coupling coefficient is $|\kappa|L=\pi\Delta nL/\lambda_B=8$.

Curves: (a) original grating, no strain.

(b) strain 0.02%.

(c) strain 0.04%.

(d) strain 0.08%.

Fig.3 Normalised group delay in the reflection looking from the large end of a taper for linear chirp as a function of the normalised detuning for different applied strains in the 125μm fibre. $|\kappa|L=8$. Time normalisation factor: $\tau_0=2nL/c$.

Curves: (a) original grating, no strain.

(b) strain 0.02%.

(c) strain 0.04%.

(d) strain 0.08%.

Fig.4 Reflectivity of a quadratic grating as a function of the normalised detuning for different applied strains in the 125μm fibre. $\kappa L=8$.

Curves: (a) original grating, no strain.

(b) strain 0.02%.

(c) strain 0.08%.

Fig.5 Normalised group delay in the reflection looking from the large end of a taper for quadratic chirp as a function of the normalised detuning for different applied strains in the 125μm fibre. $|\kappa|L=8$.

Curves: (a) original grating, no strain.

(b) strain 0.02%.

(c) strain 0.08%.

Fig. 6 Reflectivity of a phase modulated grating as a function of the normalised detuning for different strains in the 125μm fibre. $\kappa L=8$. Figure A: original grating (curve 'a') and response under a strain of 0.02% (curve 'b'). Figure B: original grating (curve 'a') and response under a strain of 0.08% (curve 'b').

Fig. 7 Reflectivity of a phase mismatched grating as a function of the normalised detuning for different strains in the 125μm fibre. $|\kappa|L=8$.

Curves: (a) original grating, no strain.

(b) strain 0.04%.

(c) strain 0.08%.

Fig. 8 Measured diameter profile of three tapers etched in fibres.

Curves: (a) Linear

(b) Quadratic

(c) Phase mismatched.

Fig. 9 Measured response of a linear grating written under a load of 53.3g, the fibre is in a relaxed state when being measured. Figure A: reflectivity. Figure B: group delay.

Fig. 10 Measured transmission coefficient of a quadratically chirped grating under different loads:

Curves: (a) 0g.

(b) 10.2g.

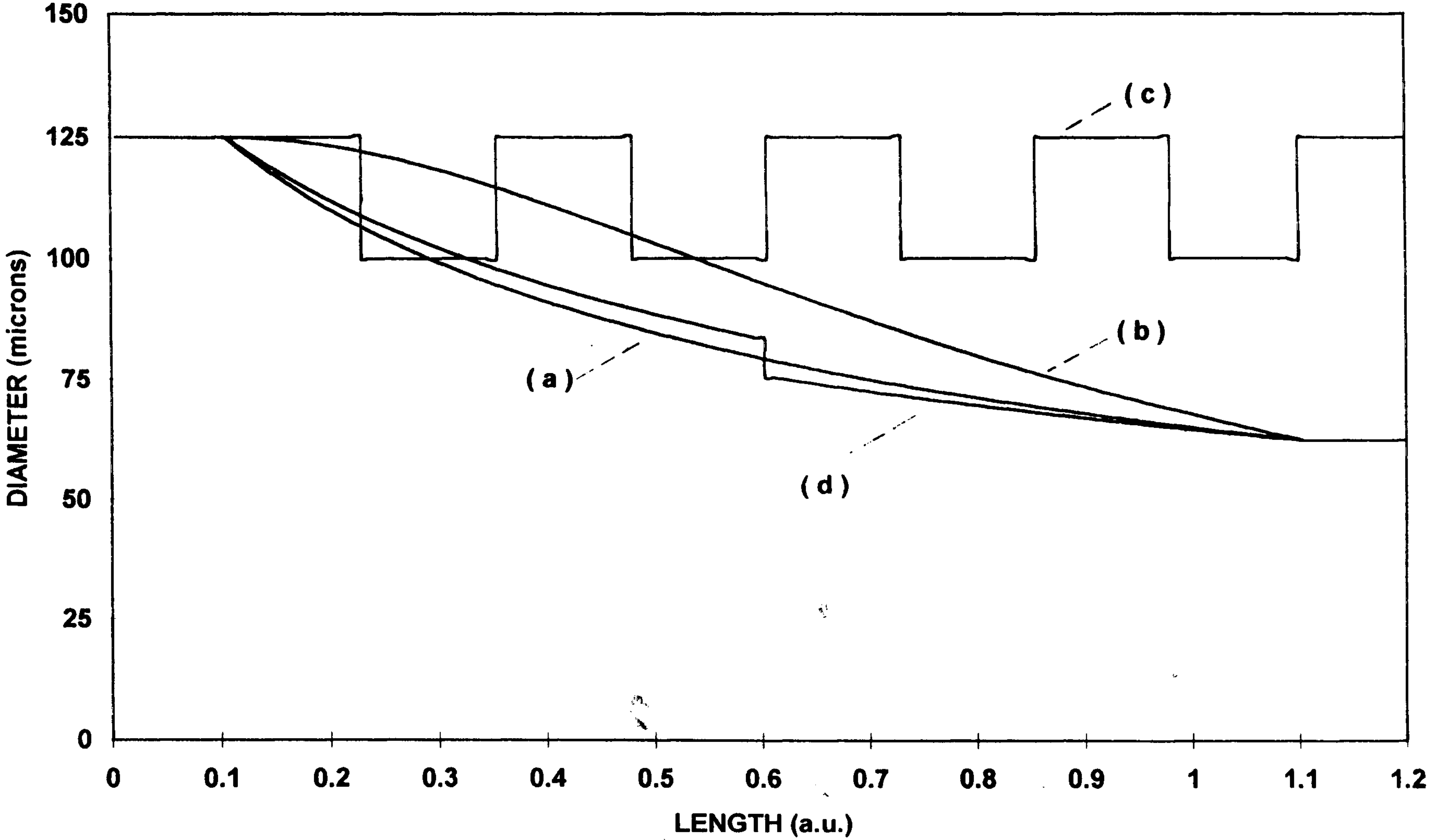
(c) 25.7g.

Fig.11 Measured transmission coefficient of a phase mismatched grating under different loads:

Curves: (a) 0g.

(b) 55.3g.

(c) 93.8g.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100
75
50
25
0
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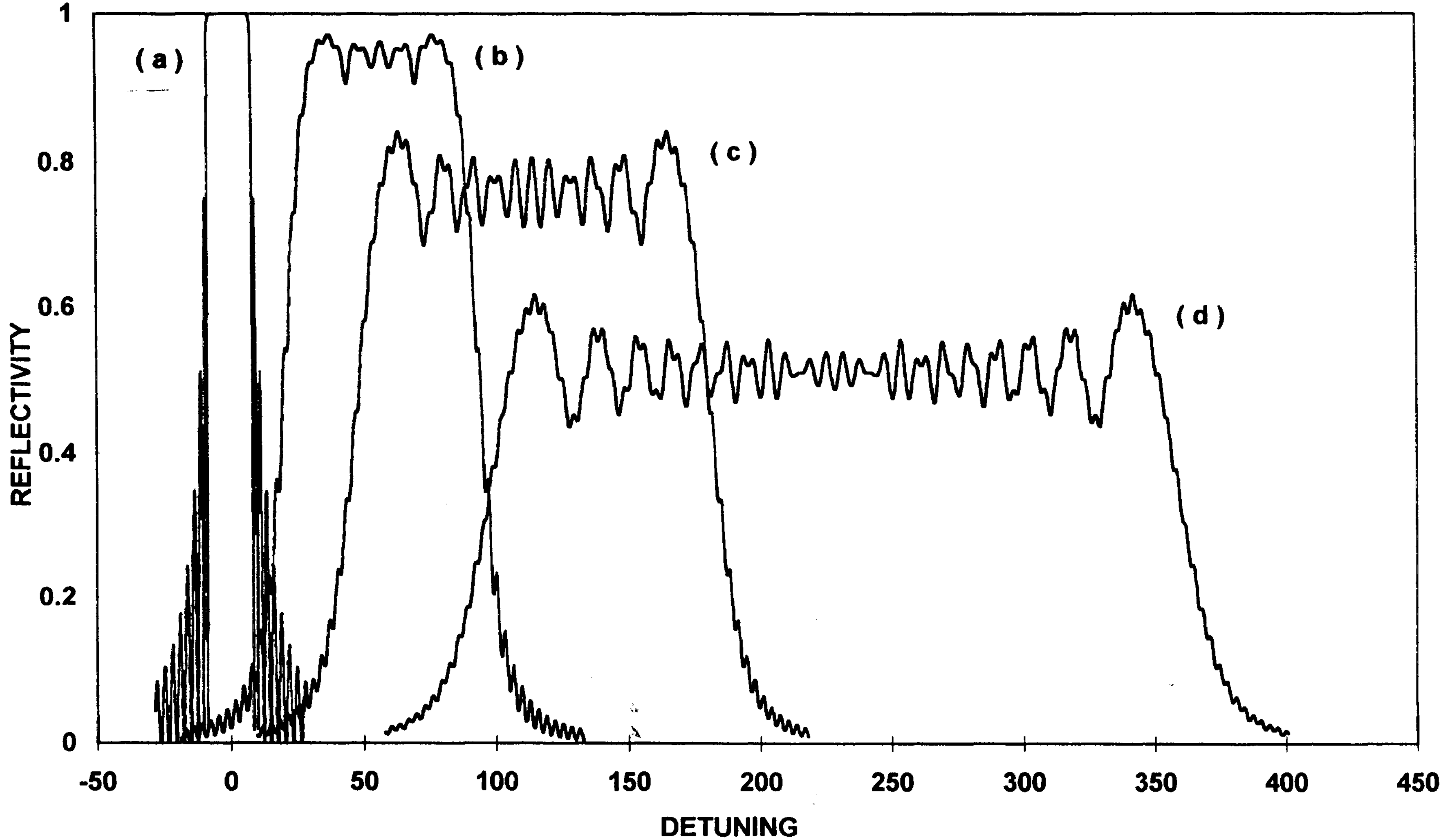
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
LENGTH (a.u.)
(a)
(b)
(c)
(d)

Figure 1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0.6
0.4
0.2
0
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0
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100
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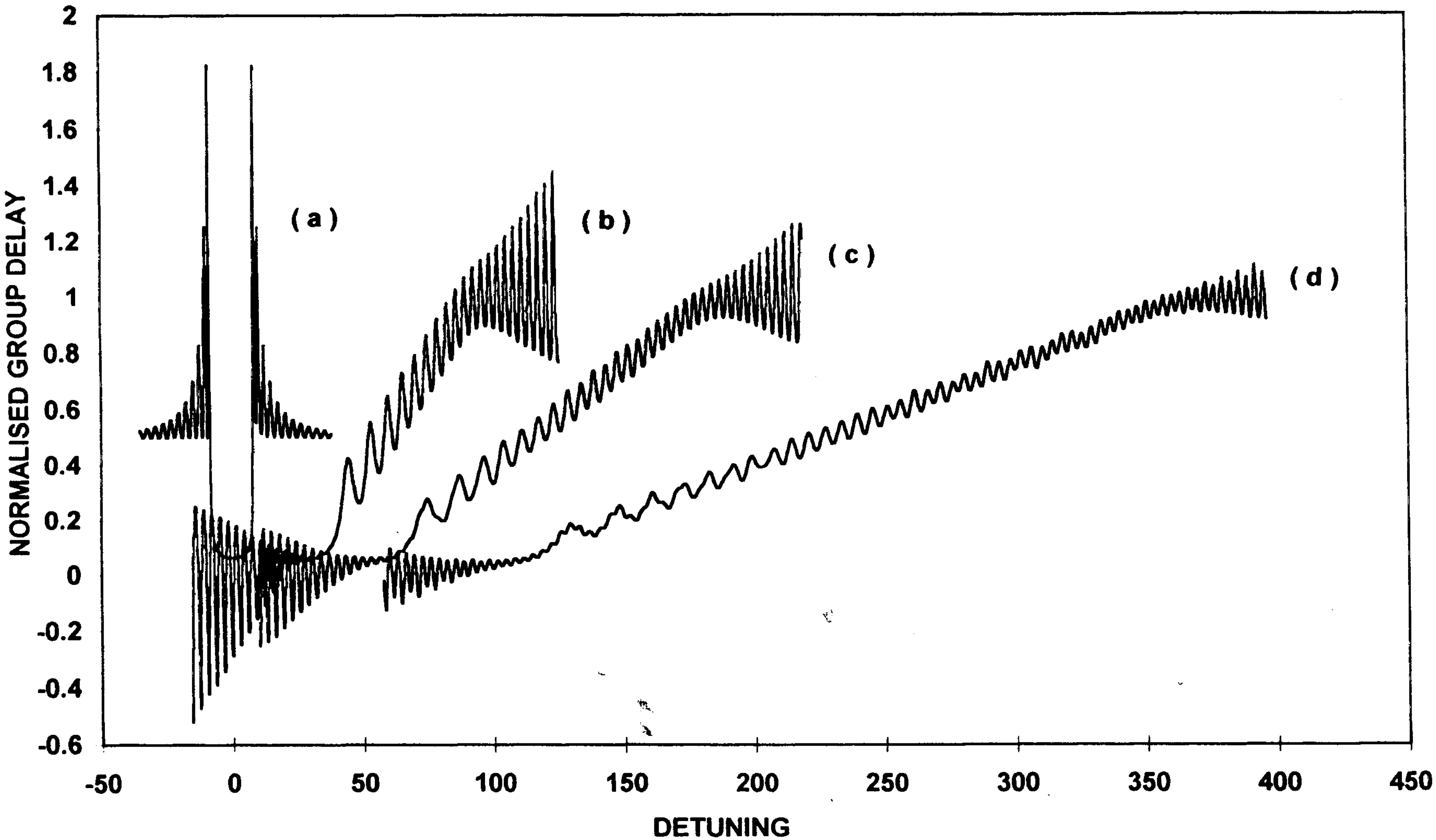
200
250
300
350
400
450
DETUNING
(a)
(b)
(c)
(d)

Figure 7


NORMALISED GROUP DELAY
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1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-50
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300
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400
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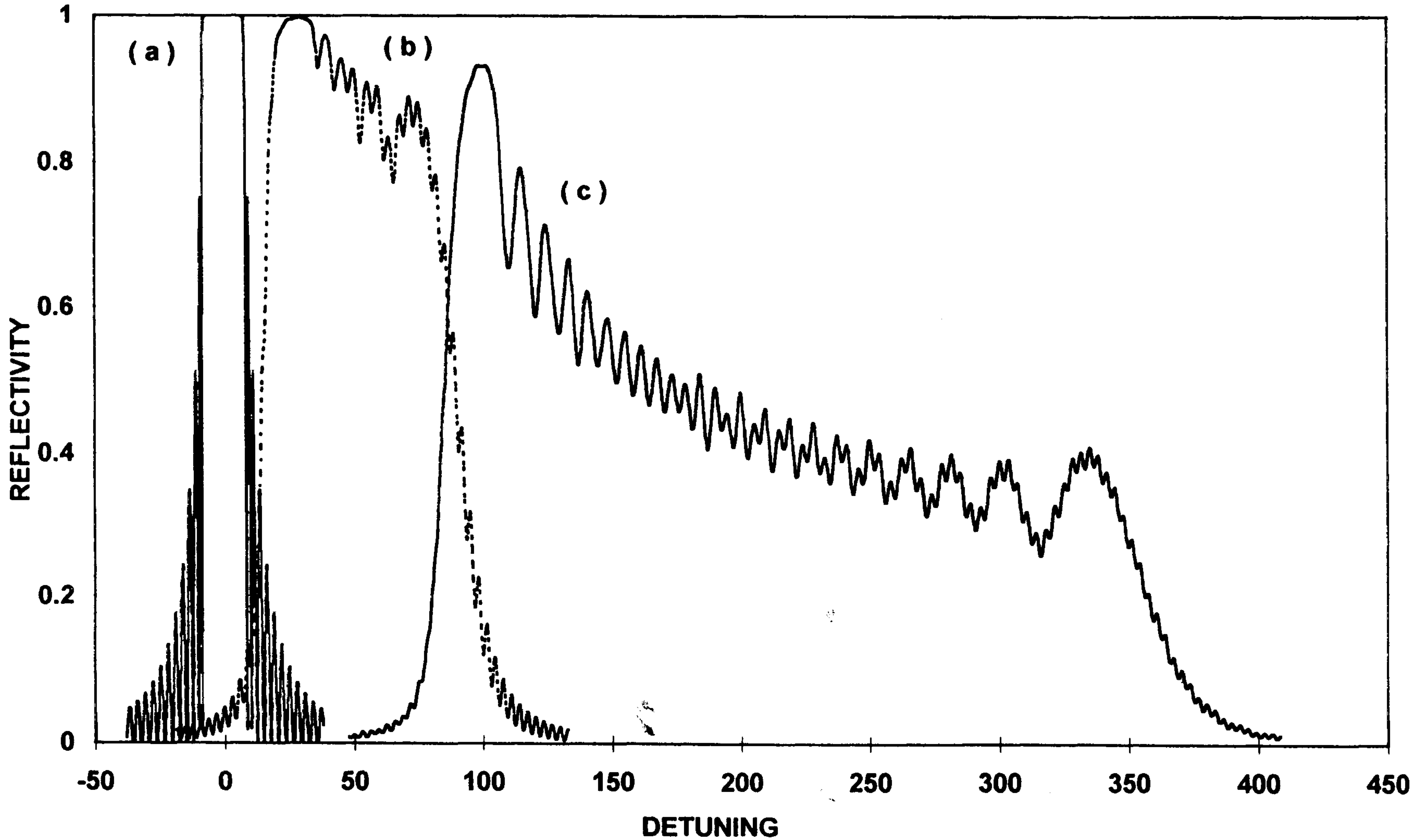
DETUNING
(a)
(b)
(c)
(d)


REFLECTIVITY
DETUNING
(a)
(b)
(c)
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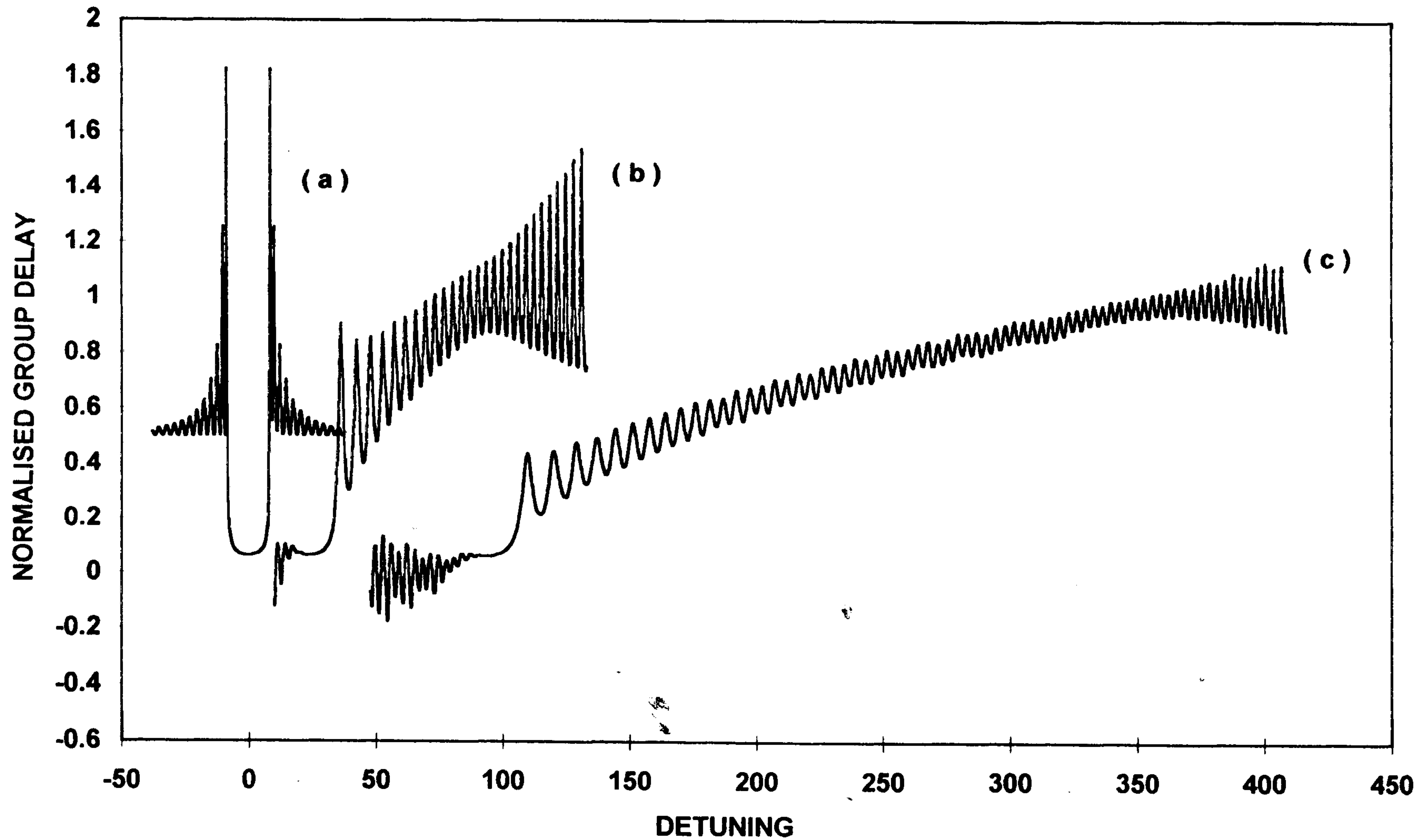
NORMALISED GROUP DELAY
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1.6
1.4
1.2
1
0.8
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0.4
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0
-0.2
-0.4
-0.6
-50
0
50
100
150
200
250
300
350
400
450
DETUNING
(a)
(b)
(c)

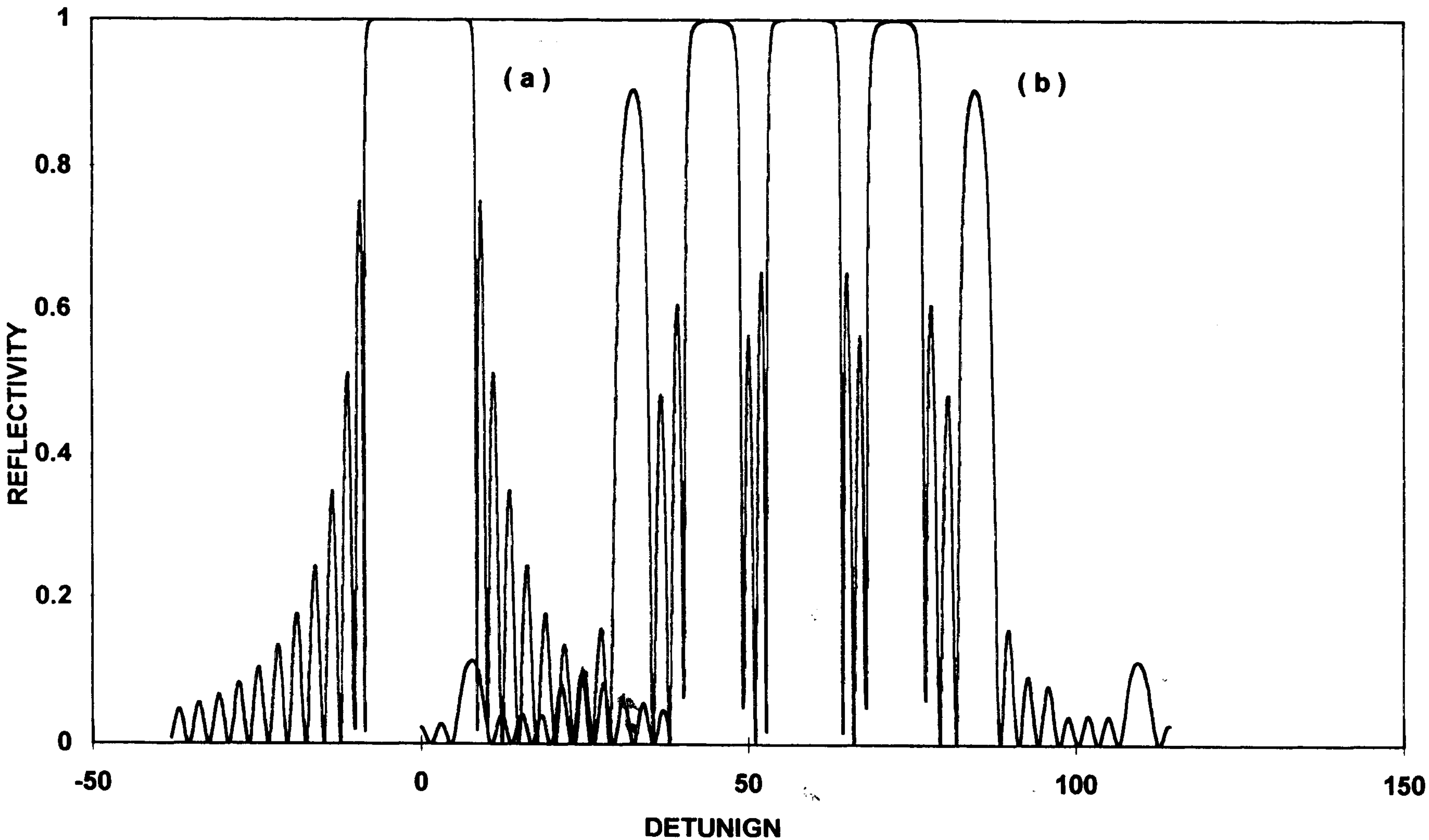


Figure 6-A

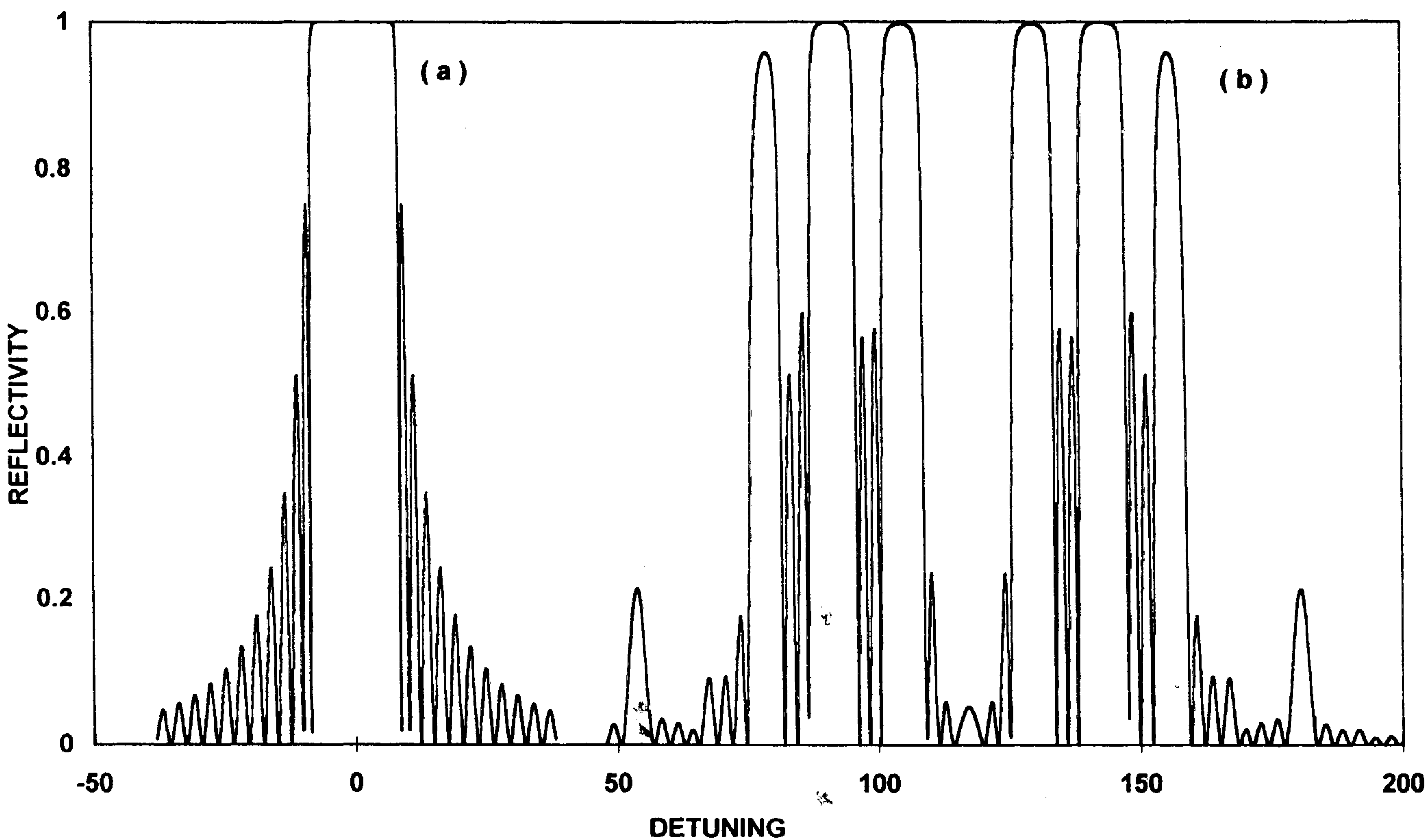


Figure 6-B

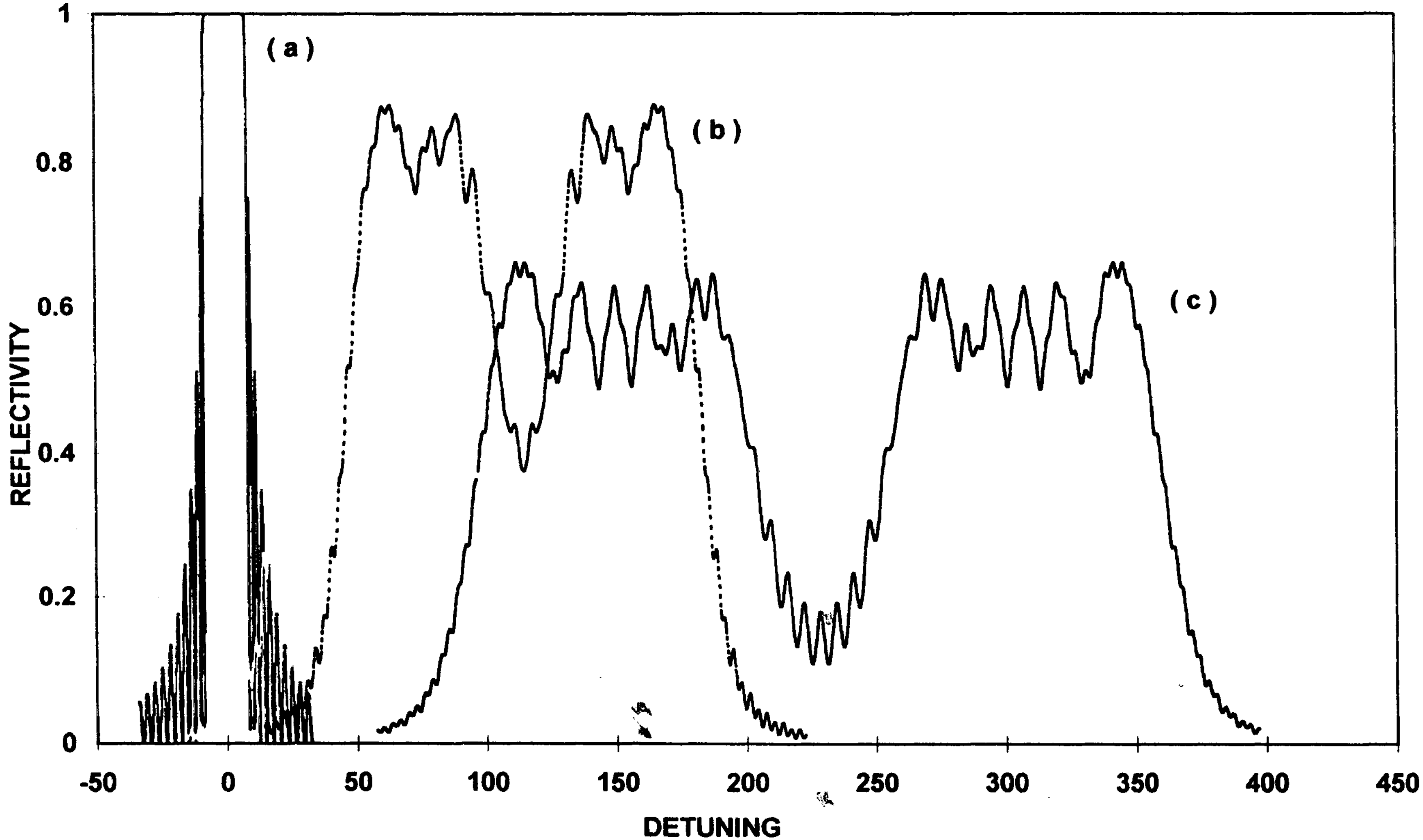

REFLECTIVITY
DETUNING
(a)
(b)
(c)
1
0.8
0.6
0.4
0.2
0
-50
0
50
100
150
200
250
300
350
400
450

Figure 7

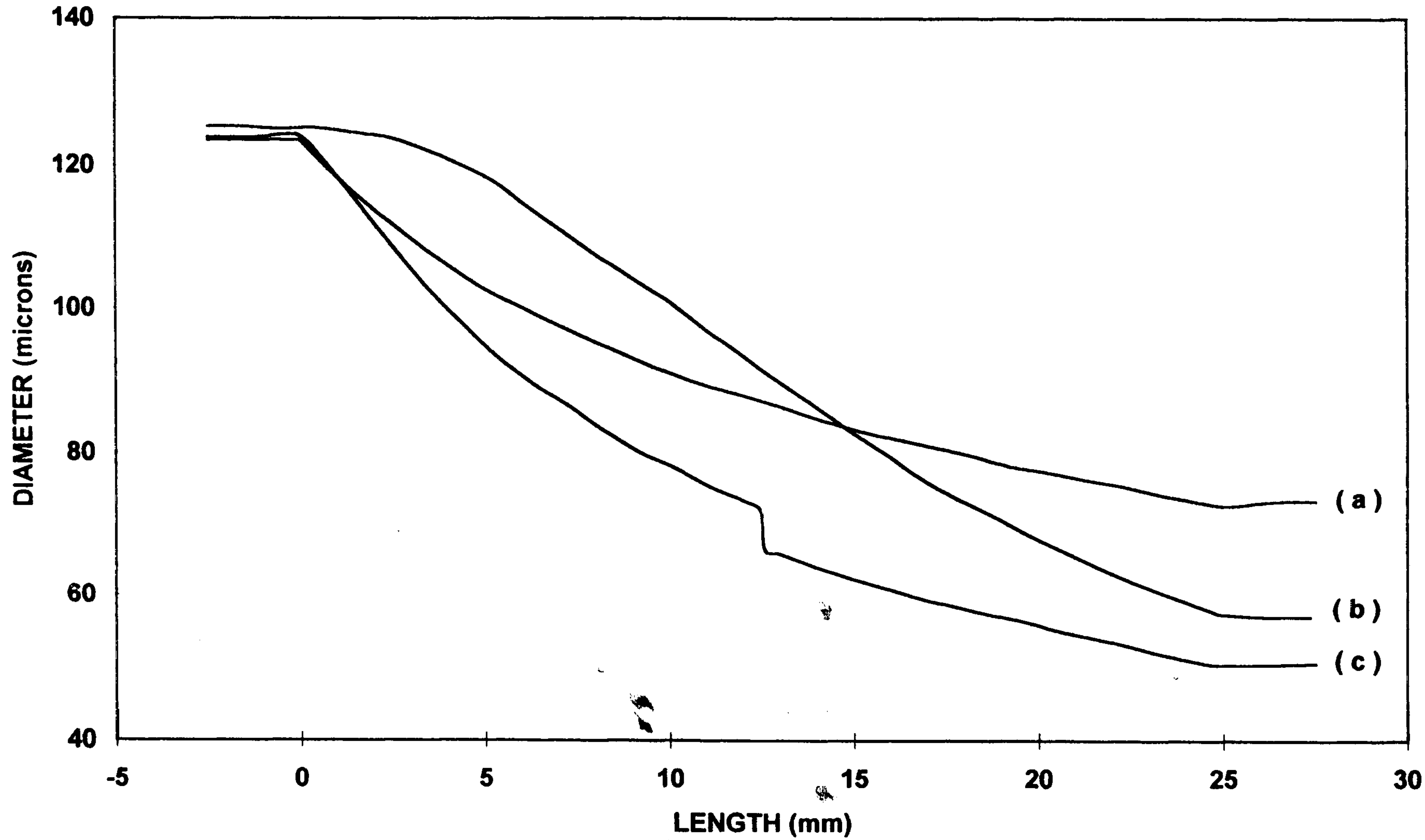

DIAMETER (microns)
140
120
100
80
60
40
-5
0
5
10
15
20
25
30
LENGTH (mm)
(a)
(b)
(c)

Figure 8

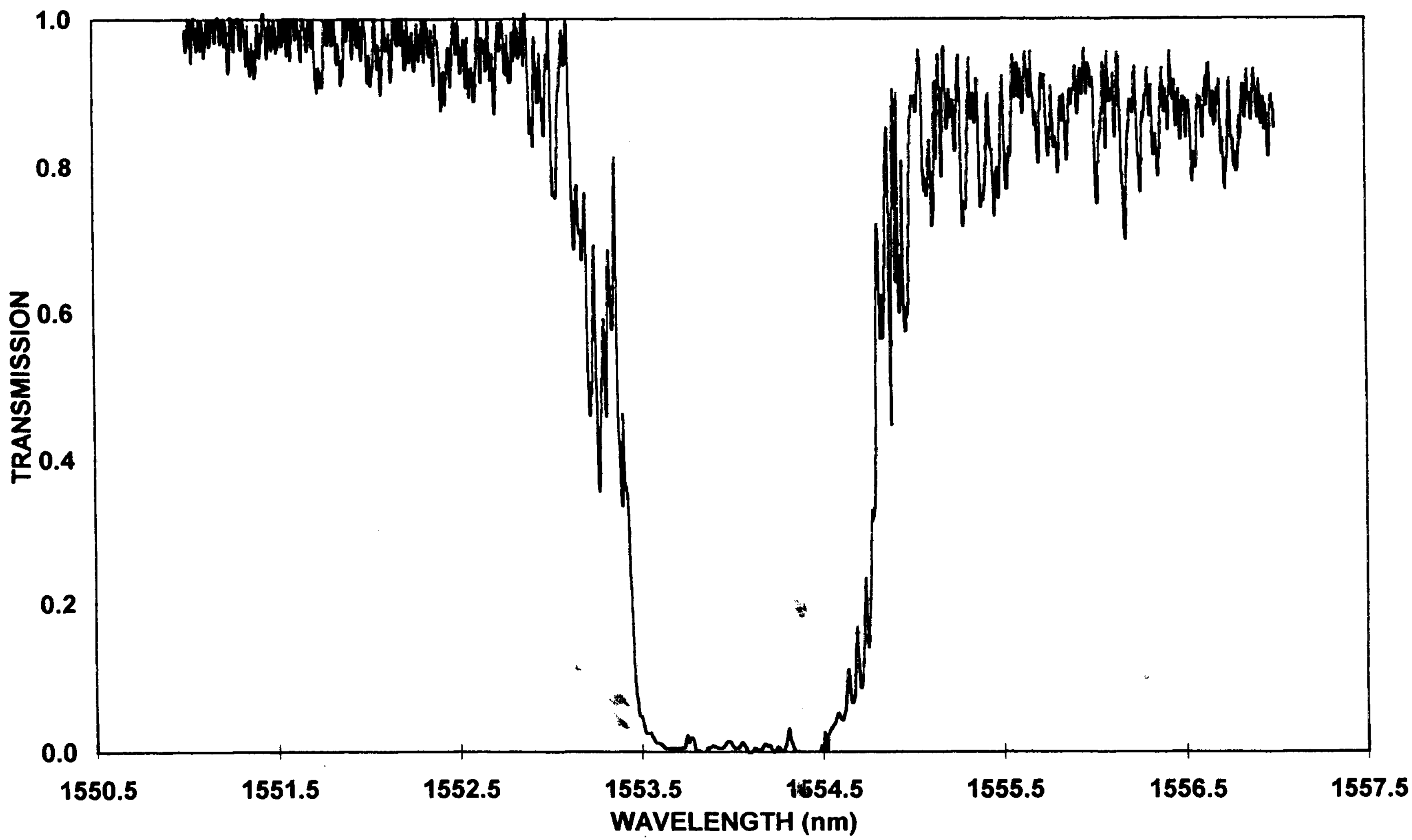

TRANSMISSION
1.0
0.8
0.6
0.4
0.2
0.0
1550.5
1551.5
1552.5
1553.5
1554.5
1555.5
1556.5
1557.5
WAVELENGTH (nm)

Figure 4-A

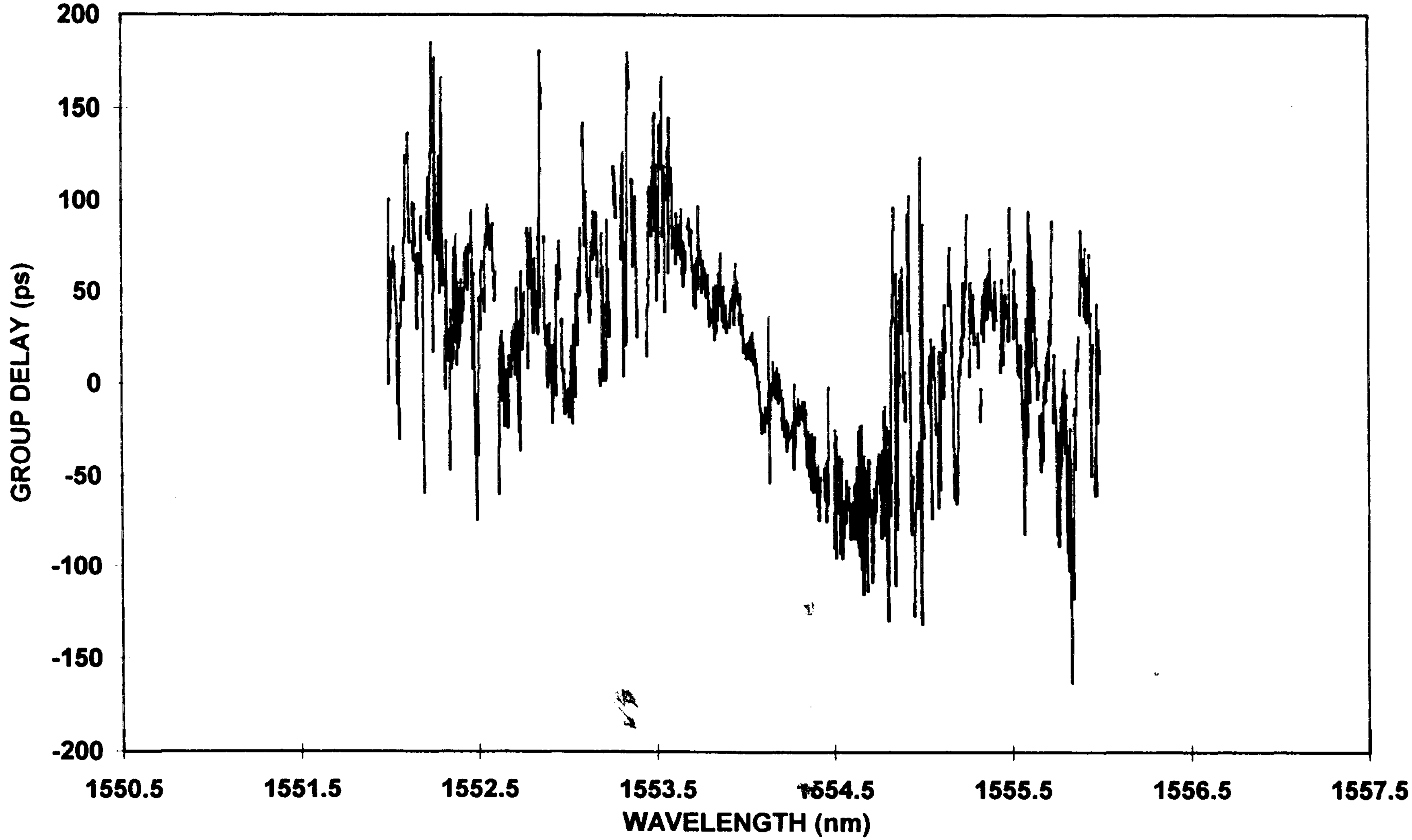
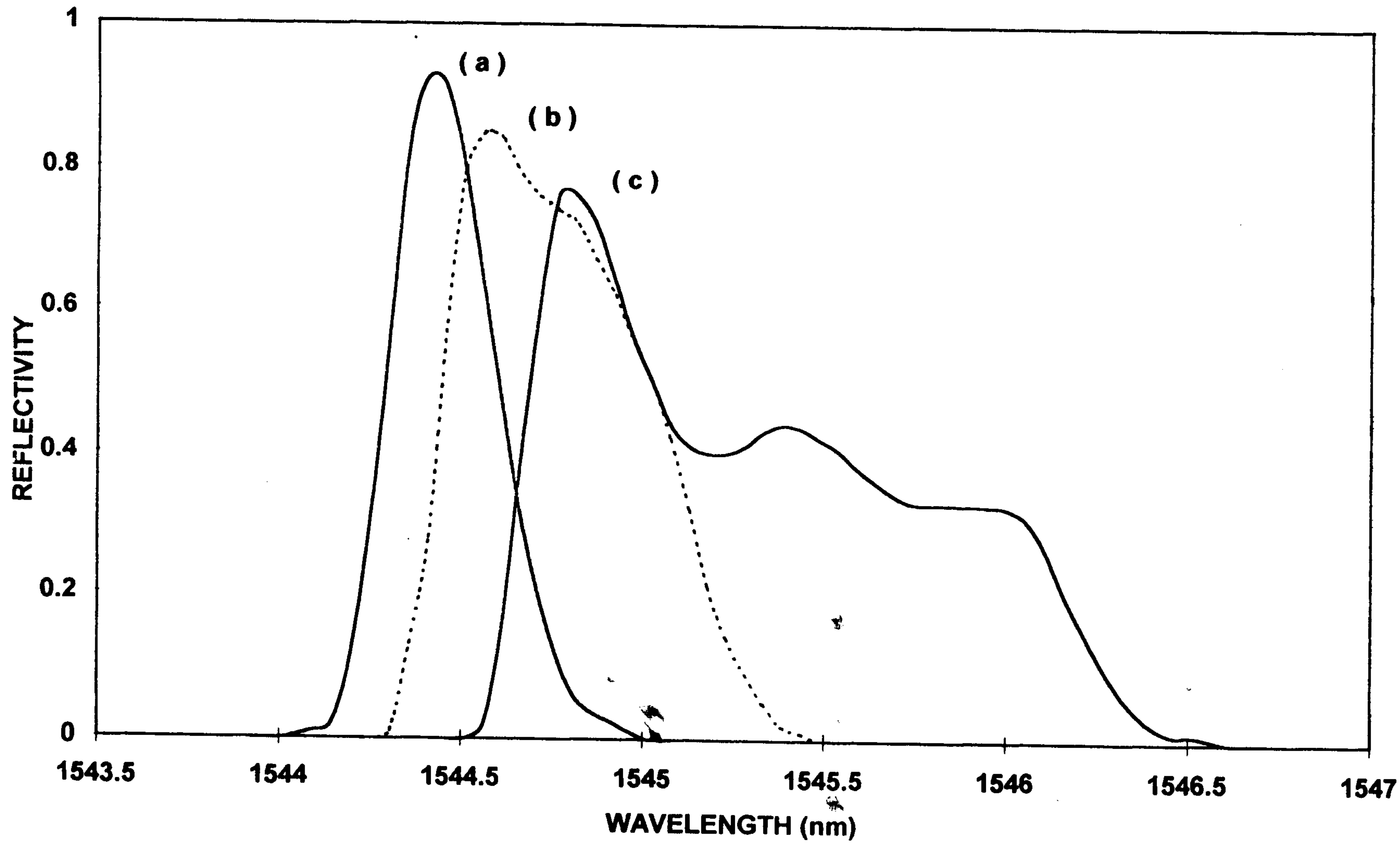

GROUP DELAY (ps)
200
150
100
50
0
-50
-100
-150
-200
1550.5
1551.5
1552.5
1553.5
1554.5
1555.5
1556.5
1557.5
WAVELENGTH (nm)

Figure 4-B



1
0.8
0.6
0.4
0.2
0
REFLECTIVITY
(a)
(b)
(c)
1543.5
1544
1544.5
1545
1545.5
1546
1546.5
1547
WAVELENGTH (nm)

Figure

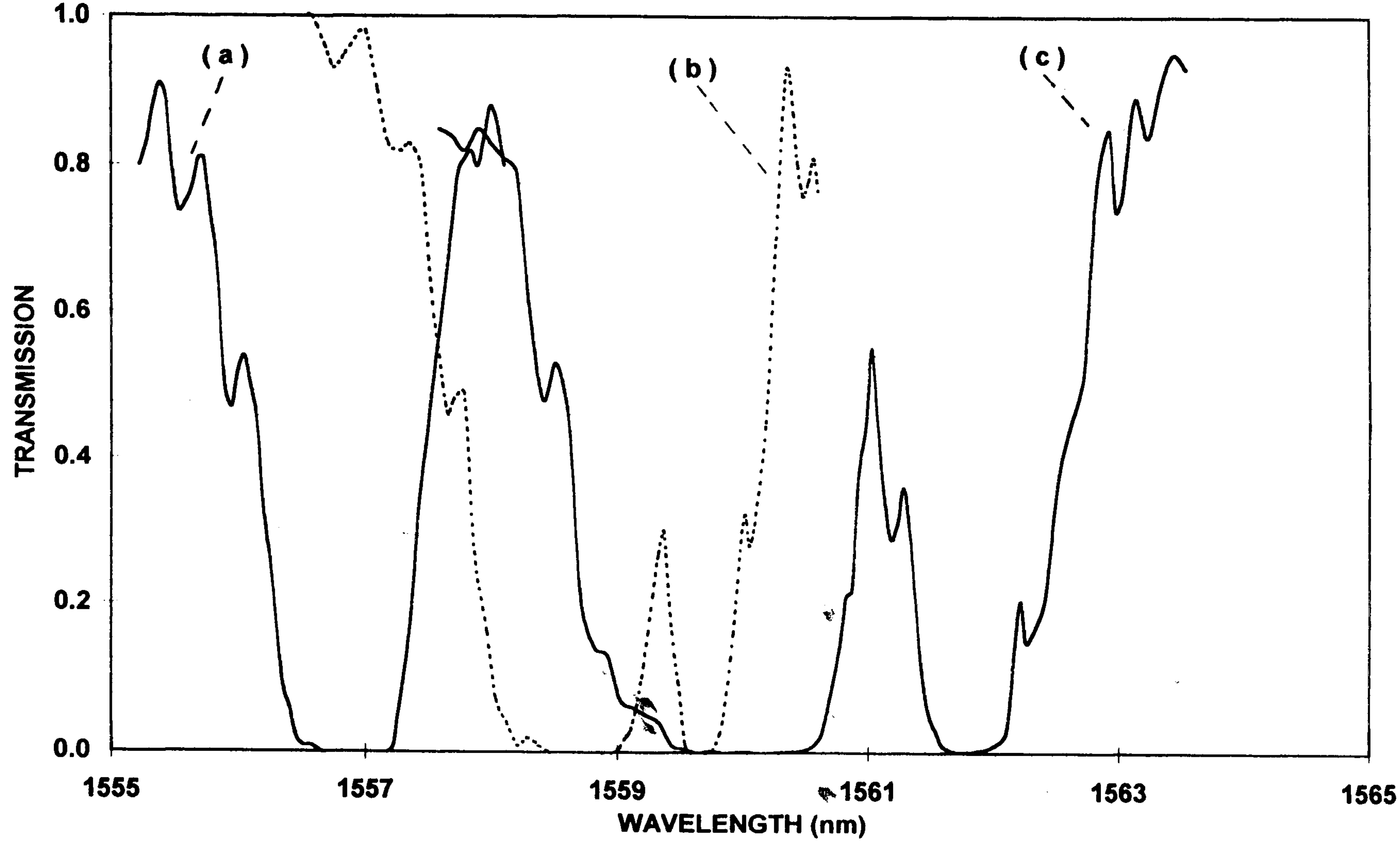

1.0
0.8
0.6
0.4
0.2
0.0
TRANSMISSION
(a)
(b)
(c)
1555
1557
1559
1561
1563
1565
WAVELENGTH (nm)

Figure 11