# Coupling Characteristics of Cladding modes In Tilted Optical Fibre Bragg Gratings

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**Abstract:**

We have studied both theoretically and experimentally the effect of grating tilting on the coupling between fundamental core mode and cladding modes in an optical fibre Bragg grating. The coupling is shown to be very sensitive on the tilting angle. It has also shown that tilting angle has to be minimised in fibres with designs to suppress the coupling between fundamental core mode and cladding modes. We have also studied the single strong loss peak accompanying Bragg reflection peak in depressed cladding fibres, showing a good agreement between the measured and theoretically predicted behaviour.

**Key words:** Optical fibre grating

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## I) Introduction:

There has been tremendous progress in the area of fibre Bragg gratings in the last few years. This is due to their numerous applications, especially in wavelength-division-multiplexing (WDM) systems. General characteristics of fibre Bragg gratings have been studied both theoretically and experimentally by various authors[1,2]. Characteristics of Bragg gratings and coupling between radiation mode and core mode in tilted fibre Bragg gratings have been studied by Erdogan [3]. Coupling between cladding modes and the core mode is a very important feature of fibre Bragg gratings. It gives a series of loss peaks at the shorter wavelength side of the main Bragg reflection peak. These peaks must be reduced for these gratings to be useful in WDM systems, as they introduce an out-of-band loss. Two techniques have been proposed to reduce this effect, one using a photosensitive cladding [4] and the other using a depressed cladding [5]. Cladding mode suppression by both of these techniques will be affected in a tilted gratings. The coupling between the core mode and cladding modes has also been used in long period gratings in a forward coupling scheme to achieve loss filters in gain flattened amplifiers [6]. In this paper, we will study the effect of tilting on the coupling between cladding modes and core mode. Three types of fibres are studied theoretically, one with a photosensitive core, one with a photosensitive core and equally photosensitive cladding, and a third with a photosensitive core and depressed cladding. We also experimentally studied two types of fibre; one type has a photosensitive core and the other has a photosensitive core and depressed cladding.

## II) Theory:

We only deal with cases where the fibre core has a step index profile and the grating has a uniform index modulation over the photosensitive region. The fibre under study has a core refractive index $n_{co}$ and a cladding refractive index $n_{cl}$. The fibre is surrounded by air ($n_{air}$=1). The fibre also has a core radius of $\rho$ and a cladding radius of a. In such a structure, the electric or magnetic field of the guided fundamental mode in the core are represented by the normalised field distribution $\Psi(r, \varphi)$ in polar co-ordinates. Such a mode has its power concentrated around the core and the guidance is not affected by the cladding-air interface of the structure. This mode has a circular symmetry and has only a radial dependence on r. Many other modes exist in such a structure, due to the strong guidance by the cladding-air interface. We represent such a modal field distribution with $\Psi_{lm}(r,\varphi)$. We use approximations for a weakly guided waveguide in our study [7]. Such approximations will introduce an error for the cladding modes due to the strong guidance at the cladding-air interface. In our experience, this approximation is sufficient for the accuracy that is required in our study. This approximation allows to treat the media as polarisation homogeneous and significantly simplifies the analysis. In this case, the modal field will only have transverse electric or magnetic fields and we can use the standard linearly polarised mode representation.

Tilting a grating in a fibre is equivalent to introducing a spatially dependent phase $\Phi(r,\varphi,\theta)$ in the grating, with a tilting angle of $\theta$, grating pitch of $\Lambda$ and uniform refractive index modulation of $\Delta n_{mod}$. Throughout this paper, the angle $\theta$ is referred to the plane perpendicular to the fibre axis in the fibre, not to be confused with the angle of the writing fringe lines relative to the same plane outside the fibre, $\theta_{ext}$. At small tilting angles, $\theta \approx n_{co}\theta_{ext}$. The grating refractive index modulation is:

$$\Delta n = \Delta n_{mod} \cos(2\pi z / \Lambda + \Phi(r,\varphi,\theta))$$

where

$$\Delta\Phi = \frac{2\pi r \cos\varphi \tan\theta}{\Lambda}$$

Since the fundamental core mode only has a radial dependence we use $\Psi(r)$ instead of $\Psi(r, \varphi)$ to represent this mode. The strength of the coupling between the two modes $\Psi(r)$ and $\Psi_{lm}(r,\varphi)$ is measured by the effective refractive index modulation of the coupling $\Delta N_{mod}$,

$$\Delta N_{mod} = \int_0^{2\pi}\int_0^{\infty} \Delta n_{mod} \Psi(r)\Psi_{lm}(r,\varphi) e^{j\Delta\Phi}\, r dr d\varphi$$

We define an overlap integral as a measure of the coupling strength between two modes due to the tilted grating:

$$OL = \int_0^{2\pi}\int_0^{\infty} \Psi(r)\Psi_{nl}(r,\varphi) e^{j\Delta\Phi}\, r dr d\varphi$$

and therefore the effective index modulation becomes:

$$\Delta N_{mod} = \Delta n_{mod} OL$$

The grating peak reflection at wavelength $\lambda$ can be easily worked out.

$$R = \tanh^2(\mathrm{K}L)$$

where L is the grating length and

$$K = \frac{\pi \Delta n_{\mathrm{mod}} OL}{\lambda}$$

The effective index modulation can therefore be used for calculation of grating characteristics. OL can be used as a relative measure of the coupling strength between two modes without having to consider its absolute strength. It is determined by the modal distribution of the two modes involved and the distribution of the grating. We will use this overlap to study the effect of tilting in a fibre grating. In the theoretical study we assume a cladding refractive index of 1.45 and a Bragg wavelength of 1.55 μm. We only study the lowest two sets of the cladding modes with l=0 and 1. In each case we studied for m up to 21.

**II.1) A fibre with only a photosensitive core**

The first fibre studied has a $\Delta n$ of 0.00539, $\rho$ of 3.83 μm and a of 62.5 μm. The overlap for tilting angle from 0 to 8 degrees is plotted in figure 1. Coupling is not expected to happen between the fundamental core mode and the asymmetrical cladding mode $LP_{1m}$ due to the symmetry constraint for zero tilting angle. The coupling into the asymmetrical $LP_{1m}$ modes however quickly overtakes the strength of the coupling into the symmetric $LP_{0m}$ modes as tilting is introduced. At $\theta \approx 2$ degree, the coupling strength for the two sets of modes is almost equal. The cladding mode which couples the strongest with the fundamental core mode happens at increasingly larger m number as the tilting angle increases.

**II.2) A fibre with a photosensitive core and equally photosensitive cladding**

The fibre studied has a $\Delta n$ of 0.00539, $\rho$ of 3.83 μm and a of 62.5 μm. The fibre also has a photosensitive cladding out to twice the core radius and equally photosensitive to the fibre core. The overlap for tilting angle between 0 and 8 degrees is plotted in figure 2. In this case, the coupling between the fundamental core mode and cladding modes is suppressed for both $LP_{0m}$ and $LP_{1m}$ modes to a very small value (<0.02) in non-tilted gratings. Fibre with this design has been demonstrated for use in WDM systems [4]. The strong suppression of coupling into cladding modes is only true when the grating tilting angle is very small. As the tilting angle increases, coupling between the core mode and $LP_{1m}$ cladding modes quickly increases. For tilting angles larger than 5 degrees the coupling is very similar to the previous case where only the core is photosensitive. The dependence of the overlap between the core mode and the $LP_{0m}$ cladding modes is plotted on the same graph in figure 3 for the first 20 $LP_{0m}$ modes. Each mode reaches a maximum at a certain tilting angle. This angle increases with m number. The same graph is plotted in figure 4 for the first 11 $LP_{1m}$ modes. In this case, the overlap increases much quicker when the tilting angle increases and decreases much quicker after the maximum as tilting angle further increases. The peak transmission of an initially 30 dB grating is plotted against tilting angle together with that for the cladding mode $LP_{14}$, which has the strongest coupling at small tilting angles. As can be seen in figure 5, the coupling between the core mode and the $LP_{14}$ mode can introduce a loss of ~1.5 dB for a tilting angle as small as 0.5 degree in such a fibre design.

### II.3) A fibre with depressed cladding

In a depressed cladding fibre, $\Delta n_{cl}$ is the refractive index difference between that of the silica and the depressed cladding, $\Delta n_{co}$ is the refractive index difference between that of silica and the core, and d is the thickness of the depressed cladding region. The depressed cladding region is next to the core. The fibre that we studied has $\Delta n_{cl}$ of -0.01, $\Delta n_{co}$ of 0.012, d of 10 μm , ρ of 3.3 μm and a fibre diameter of 100 μm. This fibre becomes single mode for wavelengths above 1.16 μm due to the depressed cladding structure. Fibres with depressed cladding have been proposed to suppress coupling into cladding modes in fibre Bragg gratings. This is primarily due to the tight confinement of the guided core mode in such a structure, which allows gratings to be easily written over the area that the guided fundamental mode occupies. Good suppression of coupling from the core mode to cladding modes has been demonstrated [5]. However, as in the case of the photosensitive cladding, this suppression is only valid when the grating is not tilted. In the case of a tilted grating, strong coupling can happen to a single cladding mode which has a modal distribution very similar to that of the leaky $LP_{11}$ core mode over the core region with most of its power in the core. Coupling into this ghost mode was first reported by Morey et al [8]. It was identified by Hewlett et al that the mode is an asymmetric $LP_{16}$ cladding mode in their structure [9]. The identification of this mode in fact varies with fibre structure. In our fibre, this ghost mode is $LP_{17}$ cladding mode. As this mode is primarily guided by the core and cladding interface, the coupling between the core mode and this ghost mode is virtually unaffected by the condition of the cladding/air interface. It has been proposed to use this property in long period gratings where a grating of period of a few hundred micrometers can be used to couple from the core mode to the forward propagating ghost mode to create a single loss peak in the fibre transmission [10]. This peak does not rely on the guidance provided by the glass/air interface as a normal cladding mode would. The fibre can therefore be coated afterwards. This kind of loss filter is very important for flattening the gain spectrum of erbium doped fibre amplifiers to be used in WDM systems.

As the modal distribution of the ghost mode very much resembles that of the leaky $LP_{11}$ core mode, we use the $LP_{11}$ mode to simplify our analysis. We only consider the case where the fibre core alone is photosensitive. The dependence of overlap on the tilting angle for both Bragg reflection and the ghost mode coupling is shown in figure 7. It can be seen that the overlap of the ghost mode coupling increases very quickly from zero at zero tilting angle to more than that of the Bragg reflection at ~3.5 degree tilting angle. At ~7.8 degree tilting angle, the Bragg reflection goes to zero while the ghost mode coupling still maintains a reasonably high level. The Bragg grating at this tilting angle will not reflect and only has a narrow band loss peak in the transmission. This may be used to create single band loss peaks of a fraction of nanometers in bandwidth and can very useful for gain flattening for sharp gain features.

For an initially 30 dB Bragg grating, the strength of the Bragg grating and the ghost mode coupling is plotted in figure 8 for small tilting angles. For a tilting angle as small as 0.5 degree, the ghost mode coupling can be as strong as 1.6 dB. For grating filters for WDM systems, care has to be taken to minimise tilting angle to ensure a low out-of-band loss in these filters.

**III) Experimental results**

We studied two types of fibres. The first two fibres have a boron co-doped germanosilicate photosensitive core and non-photosensitive cladding. Fibre No.1 has $\Delta N$ of 0.011, $\rho$ of 3.0 μm, and cladding diameter of 80 μm. Fibre No.2 has the same parameters as the fibre in section II.1. Fibre No.3 is a depressed cladding fibre having the same parameters as the fibre used in section II.3. Fibre No.3 has a germanosilicate photosensitive core and a boron doped depressed cladding region.

**III.1) The fibre with only a photosensitive core**

A grating was written in fibre No.1 using an interferometer with a 248 nm KrF excimer laser without hydrogenation. No tilting was introduced. The grating was subsequently immersed in media with different refractive indeces. The results are shown in figure 9. As the refractive index of the surrounding medium increases but keeps below that of the cladding, the cladding resonance moves towards longer wavelength with higher order modes being affected more than lower order modes. This is due to the fact that the higher order modes are strongly guided and therefore more confined to the glass region. The coupling strength of the higher order cladding modes are also seen to decrease as the index difference between the surrounding media and the fibre narrows. A broad band radiation mode loss is also seen overlapping the cladding mode resonance. When the refractive index of the surrounding medium equals that of the cladding (n=1.452), the cladding mode coupling is largely suppressed and only a broad band radiation mode loss is seen, arising from coupling of the core mode to the radiation mode continuum. As the refractive index of the surrounding medium increases further, the cladding modes become leaky. The strength of their coupling increases again with an increase in the index difference of the cladding and the surrounding media. The leaky cladding mode resonance also has broader peaks compared to their corresponding cladding mode resonance due to their less resonant nature .

Gratings were written in fibre No.2 with a ArF excimer laser at 193 nm with a phase mask which was orientated to set the external blaze angle, $\theta_{ext}$. Before the U.V. exposure the fibre was hydrogen loaded at 150 bar and 70 °C for 4 days and at the same pressure and room temperature for 2 days more in order to increase its photosensitivity. Several 8 mm long gratings were formed by 2 min exposure to the U.V. pulses at a repetition rate of 40 Hz with a pulse fluence of 150 $mJ/cm^{-2}$.

A typical transmission spectrum of a tilted grating in fibre No.2 is shown in figure 10. The features to be noted are the two sets of grating modes present, one being symmetric $LP_{0m}$ modes and the other being asymmetric $LP_{1m}$ modes. Apart from the cladding mode coupling loss, what is also seen is a board band loss due to the coupling into the radiation mode continuum. This loss typically overlaps with the resonant cladding mode coupling. From the strength of the Bragg reflection at zero tilting angle, fibre characteristics and grating parameters, the index modulation of the grating $\Delta n_{mod}$ can be deduced ($\Delta n_{mod} \approx 4 \cdot 10^{-4}$ in this case). From the strength of the cladding mode coupling peaks and the known $\Delta n_{mod}$, the overlap for each coupling can be worked out at different tilting angles. This is shown in figure 11, demonstrating a reasonably good fit with the theory apart from at zero tilting angle where a substantial coupling into the asymmetric $LP_{1m}$ modes is still seen. This is primarily due to the asymmetric nature of the writing technique using a 193 nm laser and hydrogenation technique dominating at low tilting angle. The asymmetric nature arises from to the strong absorption developed in the fibre core during the writing process at this writing wavelength

**III.2) The fibre with a depressed cladding**

Gratings were written in fibre No.1 with the ArF excimer laser using the phase mask set-up. The fibre was hydrogen loaded at 100 bar and 40 °C for 7 days. The Bragg gratings, of 8 mm length, were formed with a 30 seconds exposure at 40 Hz with a pulse fluence of 87 $mJ \cdot cm^{-2}$. In this case, the index modulation of the gratings was $\Delta n_{mod} \approx 2.8 \cdot 10^{-4}$.

The overlap of the Bragg reflection and ghost mode is again worked out for different tilting angle. This is also shown in figure 6, again demonstrating a good fit with the theory apart from at near zero tilting angle. This is again primarily due to the asymmetric nature of the writing technique.

## IV) Conclusions

The characteristics of a grating are significantly affected by the amount of tilting. We did not study the case where there is a non-uniform index change in the gratings. This case is expected to be similar to the case of tilting. The coupling from core mode to cladding modes is strongly affected by the tilting angles. In fibres designed to achieve suppression of coupling into the cladding using either a photosensitive cladding or a depressed cladding, the tilting angle has be kept to a minimum to ensure a low out-of-band loss for the gratings. The coupling from core mode to the ghost mode in a depressed cladding fibre has also been studied for different tilting angles. The Bragg reflection in such gratings can be totally suppressed for certain tilting angles, allowing the implementation of a narrow band loss filter. We suspect the non-uniform index changes observed in our grating are mainly due to the use of the 193 nm ArF excimer and hydrogen loading, as we have previously achieved good suppression of asymmetric mode coupling in the same fibres using a 248 nm KrF excimer laser in a non-hydrogenated fibre.

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**Figure captions:**

Figure 1 Cladding mode coupling strength in at different tilting angles in a fibre with a photosensitive core. The fibre has a $\Delta n$ of 0.00539, $\rho$ of 3.83 $\mu$m and a of 62.5 $\mu$m.

Figure 2 Cladding mode coupling strength in at different tilting angles in a fibre with a photosensitive core and a photosensitive cladding. The fibre has a $\Delta n$ of 0.00539, $\rho$ of 3.83 $\mu$m and a of 62.5 $\mu$m. The fibre also has a photosensitive cladding of twice of core radius thick and of equally photosensitive as the fibre core.

Figure 3 $LP_{0m}$ cladding mode coupling at different tilting angles in the fibre with a photosensitive core and cladding.

Figure 4 $LP_{1m}$ cladding mode coupling at different tilting angles in the fibre with a photosensitive core and cladding.

Figure 5 Largest peak loss due to coupling into the cladding modes in an initially 30 dB grating in the fibre with a photosensitive core and cladding.

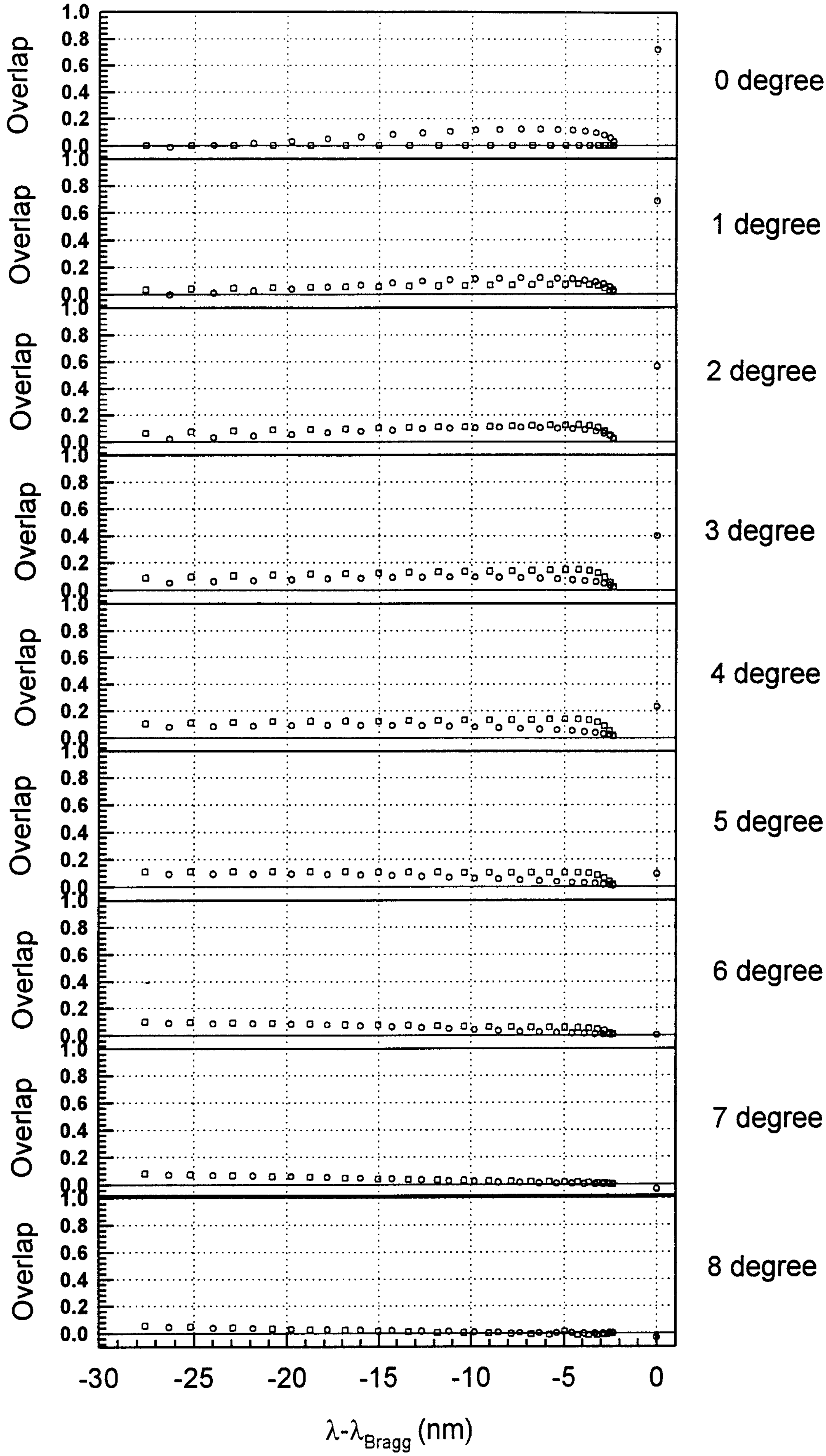
Figure 6 Dependence of the Bragg peak and ghost peak in a depressed cladding fibre. The fibre has $\Delta n_{cl}$ of -0.01, $\Delta n_{co}$ of 0.012, d of 10 $\mu$m , $\rho$ of 3.3 $\mu$m and a fibre diameter of 100 $\mu$m. Also plotted is the measured data for Bragg peak and ghost peak in the same fibre.

Figure 7 Loss due to the ghost mode coupling in an initially 30 dB gratings in the depressed cladding fibre. The fibre $\Delta n_{cl}$ of -0.01, $\Delta n_{co}$ of 0.012, d of 10 $\mu$m , $\rho$ of 3.3 $\mu$m and a fibre diameter of 100 $\mu$m.

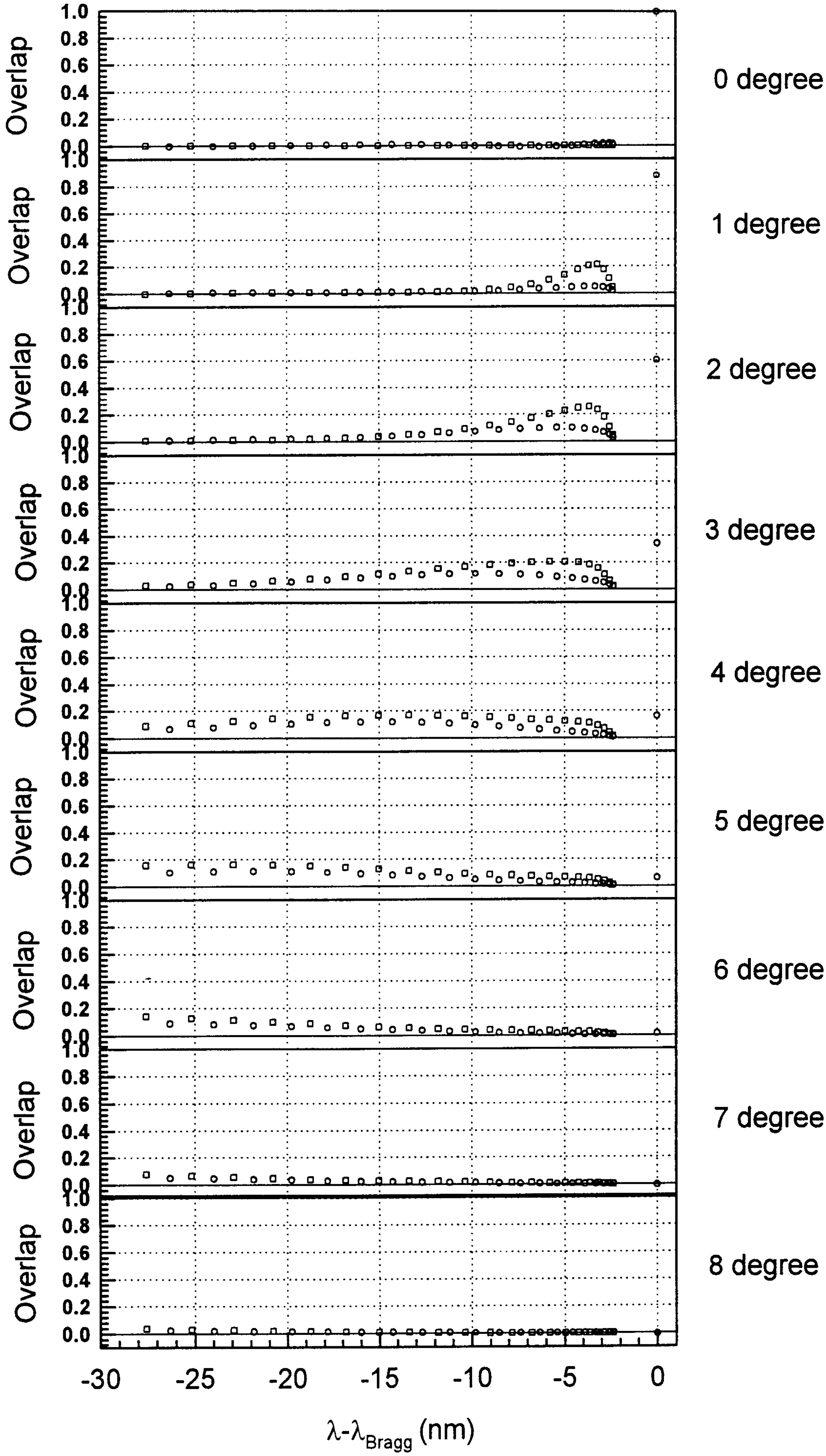
Figure 8 Measured cladding mode coupling in a untilted grating in fibre No.1 with a photosensitive core with different surrounding media. Fibre No.1 has $\Delta N$ of 0.011, $\rho$ of 3.0 $\mu$m, and cladding diameter of 80 $\mu$m.

Figure 9 Measured transmission of a tilted grating with a tilting angle of 1.16 degrees in fibre No.2. The fibre has a $\Delta n$ of 0.00539, $\rho$ of 3.83 $\mu$m and a of 62.5 $\mu$m.

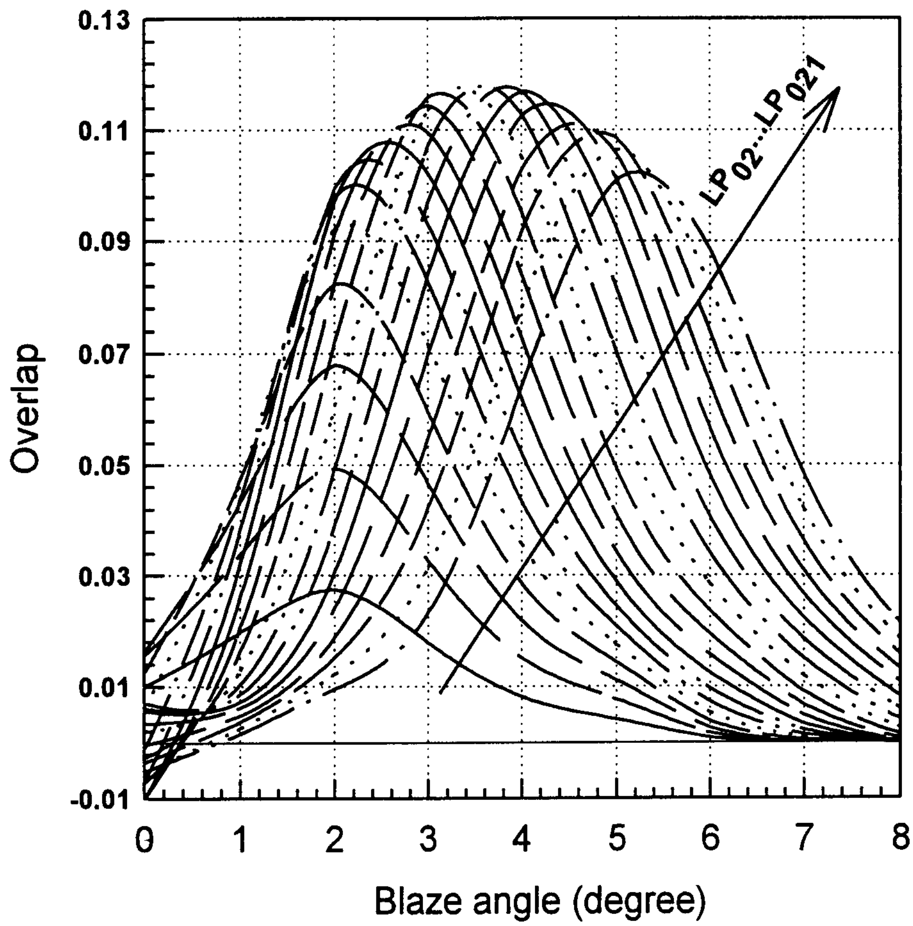
Figure 10 Measured cladding modes coupling in tilted gratings in fibre No.2. The fibre has a $\Delta n$ of 0.00539, $\rho$ of 3.83 $\mu$m and a of 62.5 $\mu$m.



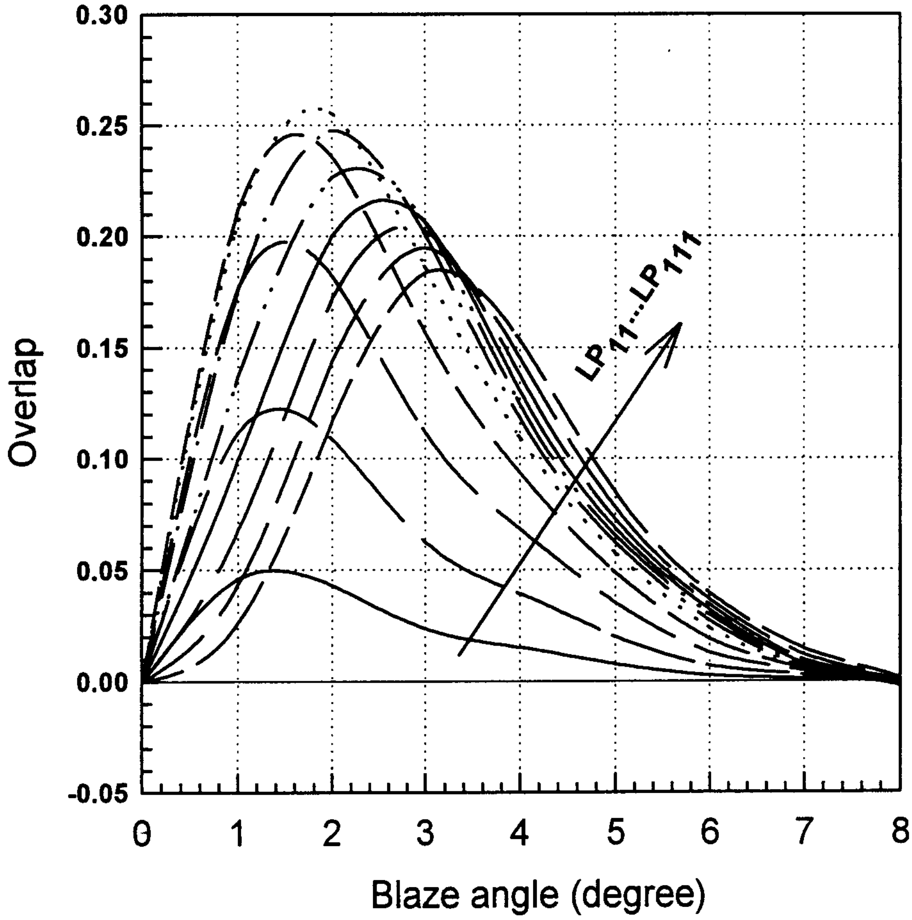
Overlap
1.0
0.8
0.6
0.4
0.2
0.0
0 degree
1 degree
2 degree
3 degree
4 degree
5 degree
6 degree
7 degree
8 degree
-30
-25
-20
-15
-10
-5
0
λ-λBragg (nm)



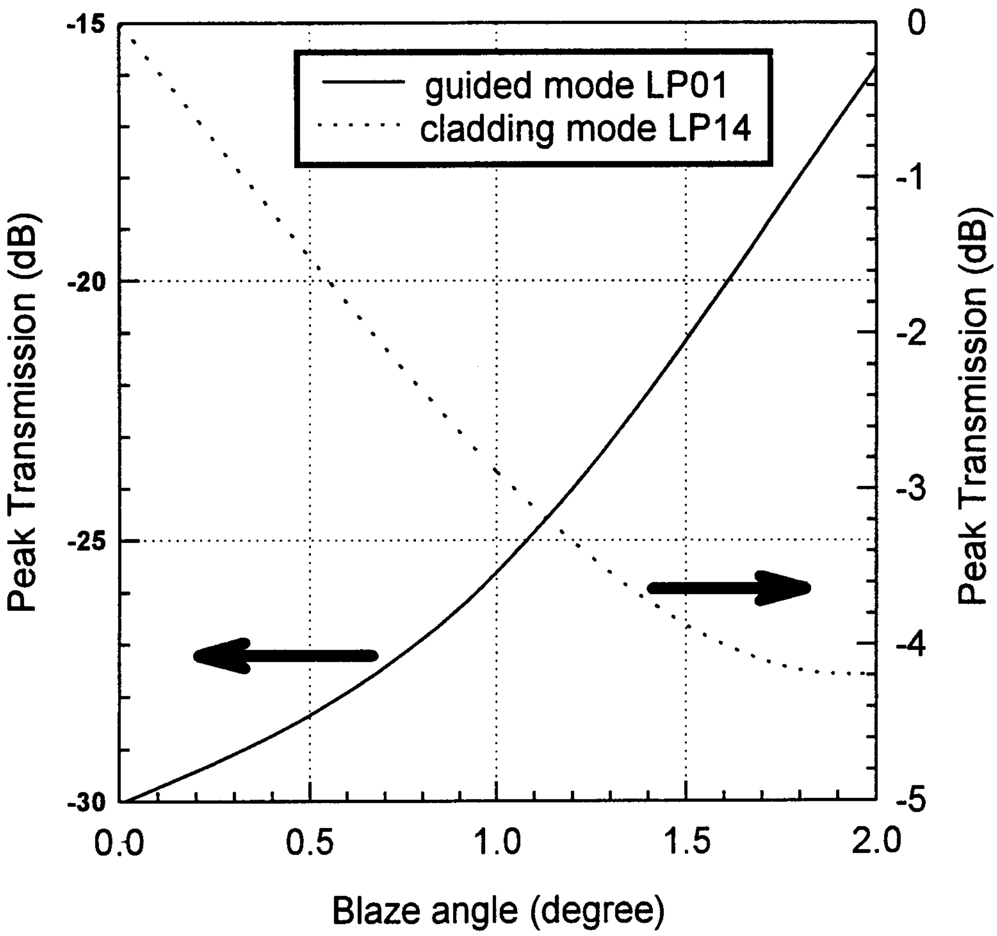
Overlap
1.0
0.8
0.6
0.4
0.2
0.0
0 degree
1 degree
2 degree
3 degree
4 degree
5 degree
6 degree
7 degree
8 degree
-30
-25
-20
-15
-10
-5
0
λ-λBragg (nm)



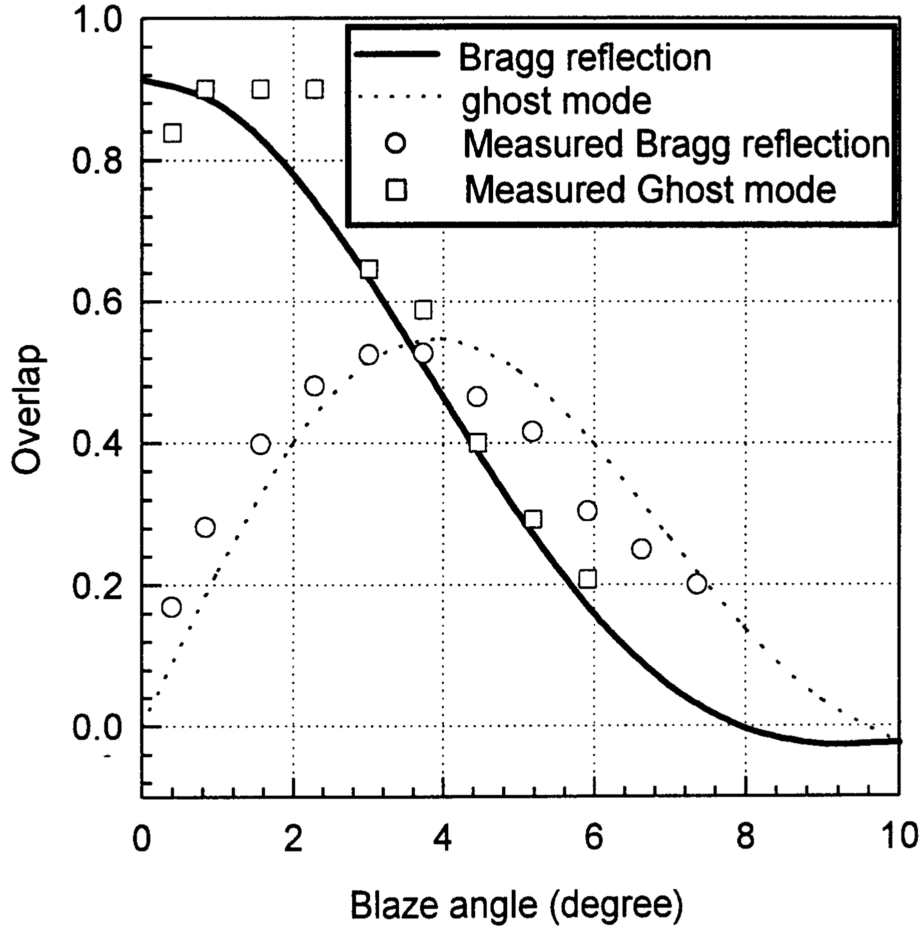
0.13
0.11
0.09
0.07
0.05
0.03
0.01
-0.01
Overlap
0
1
2
3
4
5
6
7
8
Blaze angle (degree)
LP 02...LP 021



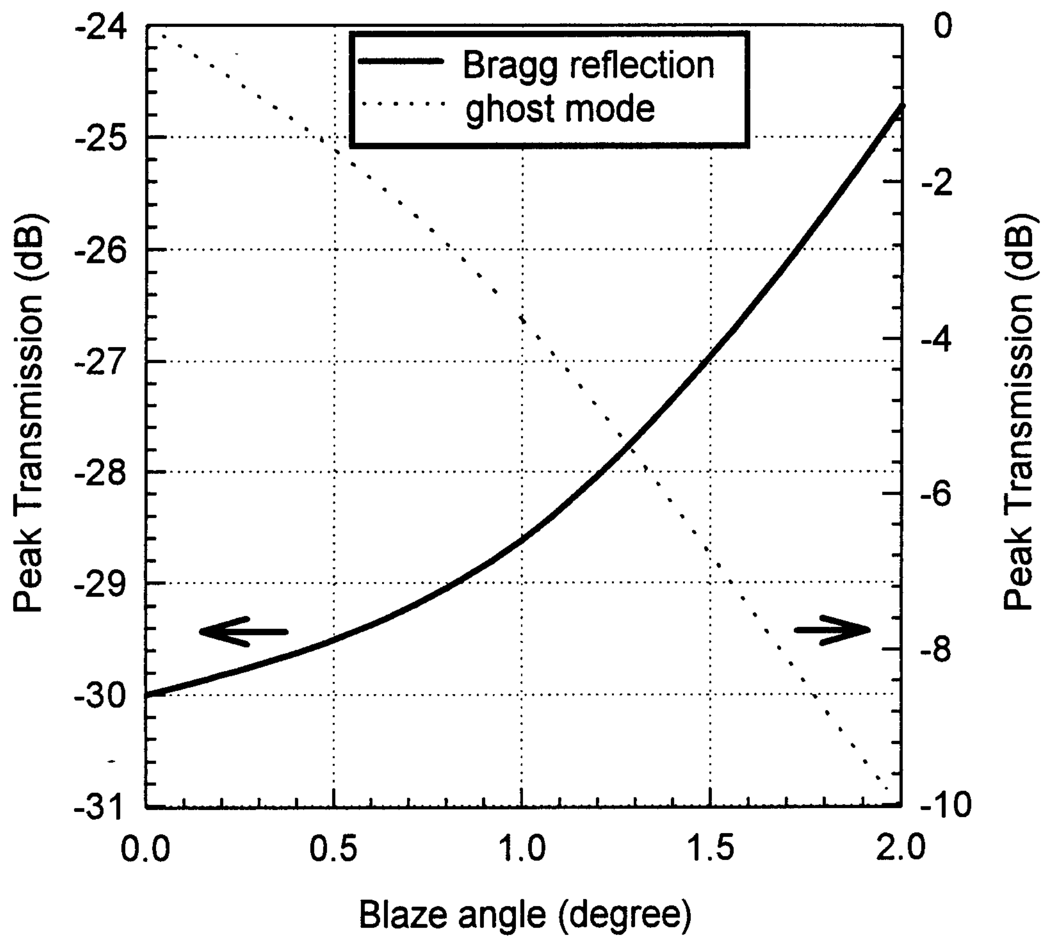
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
Overlap
0
1
2
3
4
5
6
7
8
Blaze angle (degree)
LP11...LP111



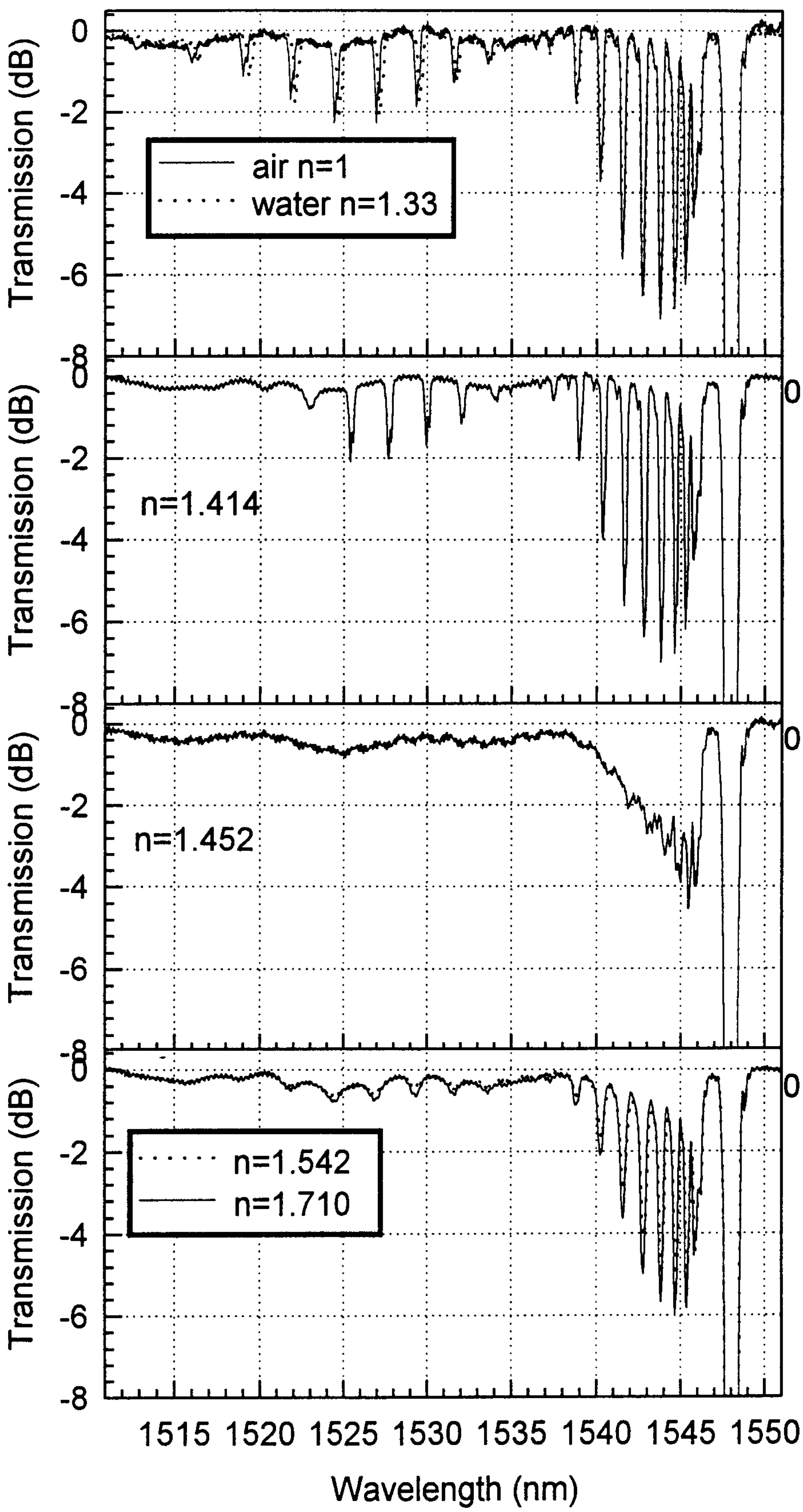
-15
-20
-25
-30
0
-1
-2
-3
-4
-5
guided mode LP01
cladding mode LP14
Peak Transmission (dB)
Peak Transmission (dB)
0.0
0.5
1.0
1.5
2.0
Blaze angle (degree)



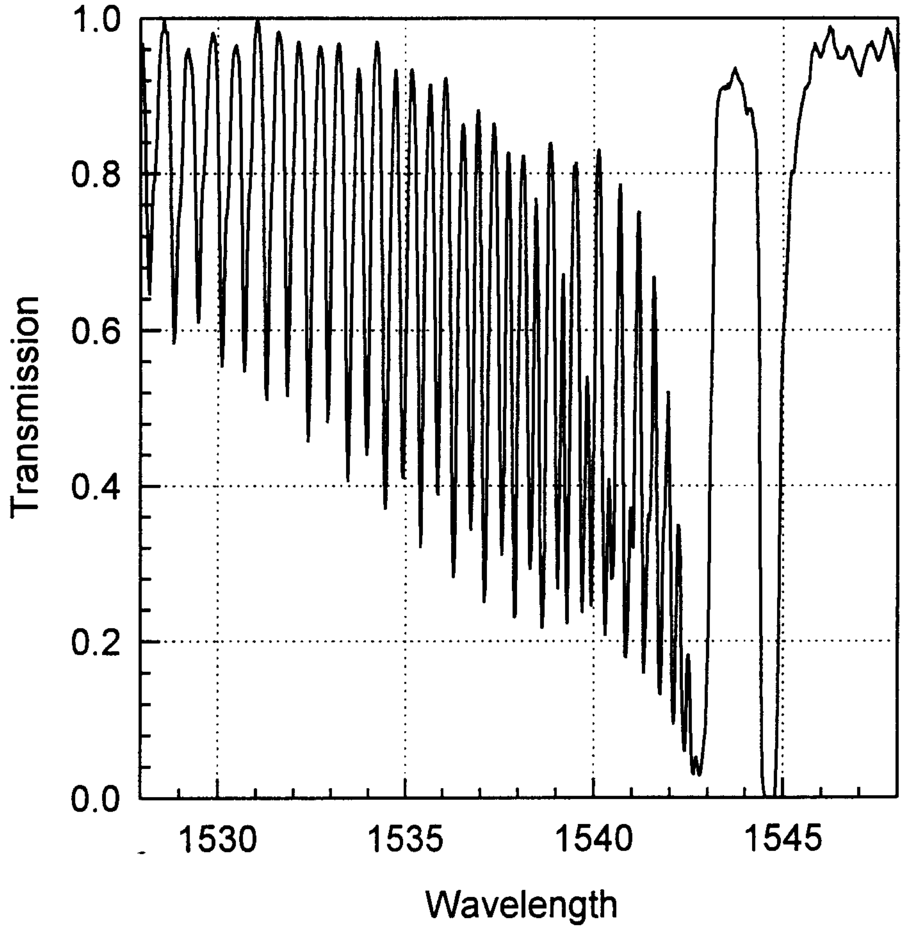
Bragg reflection
ghost mode
Measured Bragg reflection
Measured Ghost mode
Overlap
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
Blaze angle (degree)



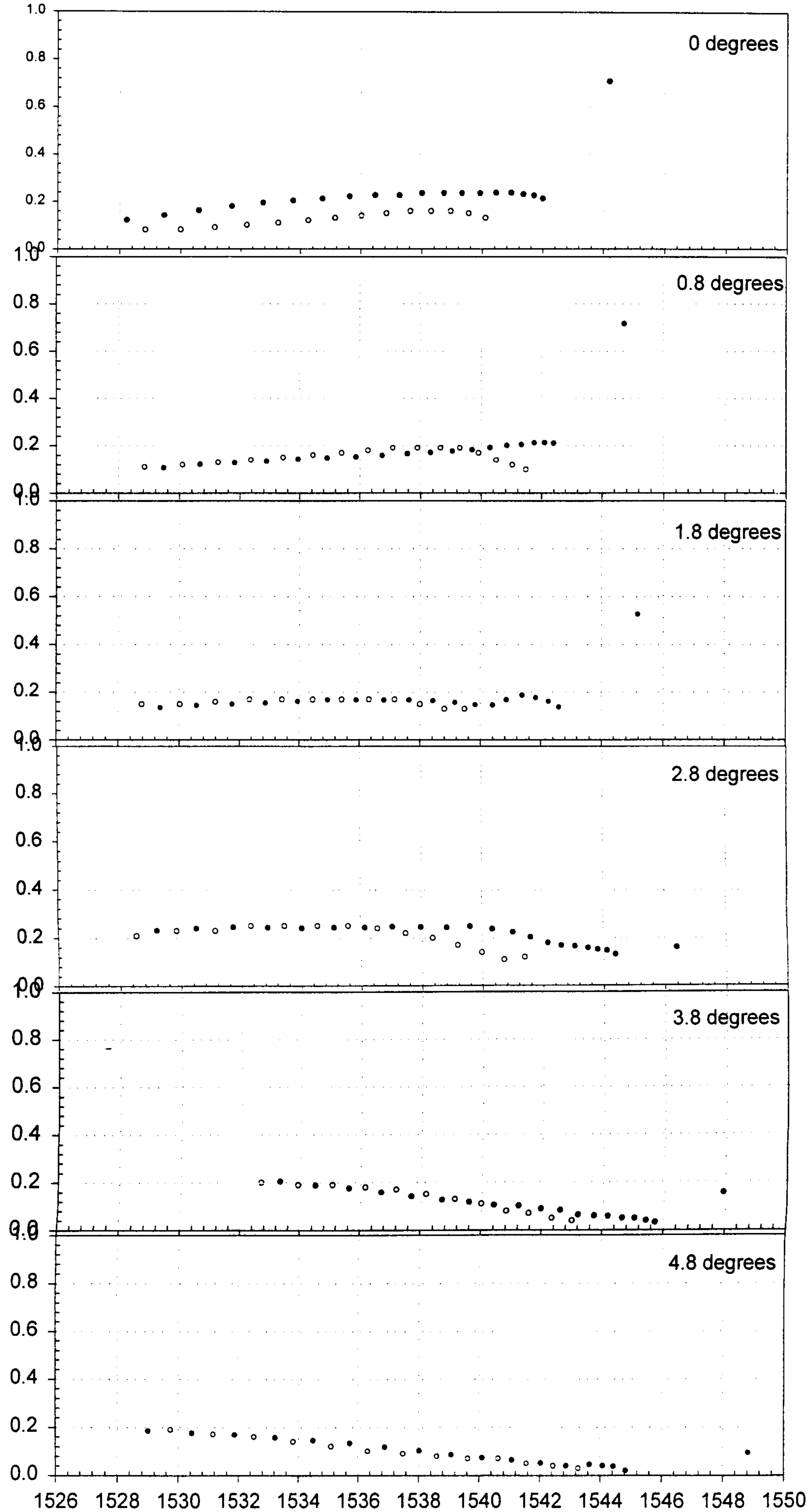
Bragg reflection
ghost mode
-24
-25
-26
-27
-28
-29
-30
-31
0
-2
-4
-6
-8
-10
0.0
0.5
1.0
1.5
2.0
Peak Transmission (dB)
Peak Transmission (dB)
Blaze angle (degree)



Transmission (dB)
air n=1
water n=1.33
n=1.414
n=1.452
n=1.542
n=1.710
0
-2
-4
-6
-8
1515 1520 1525 1530 1535 1540 1545 1550
Wavelength (nm)



1.0
0.8
0.6
0.4
0.2
0.0
Transmission
1530
1535
1540
1545
Wavelength


0 degrees
0.8 degrees
1.8 degrees
2.8 degrees
3.8 degrees
4.8 degrees
1.0
0.8
0.6
0.4
0.2
0.0
1526
1528
1530
1532
1534
1536
1538
1540
1542
1544
1546
1548
1550