

# Experimental study on the origin of optical waveguide losses by means of Rayleigh backscattering measurement

I. Salinas, I. Garcés, R. Alonso, J. Pelayo and F. Villuendas

Grupo de Tecnologías Fotónicas, Instituto de Investigación en Ingeniería de Aragón (ISA), Universidad de Zaragoza, 500018 Zaragoza, Spain

[isalinas@unizar.es](mailto:isalinas@unizar.es), [ngarcés@unizar.es](mailto:ngarcés@unizar.es), [ralonso@unizar.es](mailto:ralonso@unizar.es), [pelayo@unizar.es](mailto:pelayo@unizar.es), [fvilluendas@unizar.es](mailto:fvilluendas@unizar.es)

**Abstract:** Scattering is often considered as the main cause of the huge attenuation difference between optical fibers and integrated optical waveguides. In order to evaluate the magnitude of scattering in those waveguides, an optical low coherence reflectometry experiment has been conducted, showing that the amount of backscattered light is not enough to explain that difference in losses.

©2005 Optical Society of America

OCIS codes: (130.0130) Integrated optics; (290.1350) Backscattering.

---

## References and Links

1. R. Adar, M.R. Serbin, V. Mizrahi. "Less than 1 dB per meter propagation loss of silica waveguides measured using a ring resonator," *J. Lightwave Technol.* **12**, 1369 – 1372 (1994).
2. F. Ladouceur. "Roughness, inhomogeneity, and integrated optics," *J. Lightwave Technol.* **15**, 1020 – 1025 (1997).
3. T. Baba, Y. Kokubun, "Scattering loss of antiresonant reflecting optical waveguides," *J. Lightwave Technol.* **9**, 590–597 (1991).
4. I. Garcés, F. Villuendas, J. Vallés, C. Domínguez, M. Moreno. "Analysis of leakage properties and guiding conditions of rib antiresonant reflecting optical waveguides," *J. Lightwave Technol.* **14**, 798–805 (1996).
5. I. Garcés, J. Subías, R. Alonso. "Analysis of the modal solutions of rib antiresonant reflecting optical waveguides," *J. Lightwave Technol.* **17**, 1566-1574 (1999).
6. K. Takada, S. Mitachi. "Measurement of depolarization ratio and ultimate limit of polarization crosstalk in silica-based waveguides by using a POLCR," *J. Lightwave Technol.* **16**, 639-645 (1998).
7. E.G. Neumann. *Single-Mode Fibers. Fundamentals*. (Springer Verlag, 1988), Chap. 13.4.
8. R. C. Youngquist, S. Carr, and D. E. N. Davies, "Optical coherence- domain reflectometry: A new optical evaluation technique," *Opt. Lett.* **12**, 158-160 (1987).
9. K. Takada, I. Yokohama, K. Chida, and J. Noda, "New measurement system for fault location in optical waveguide devices based on an interferometric technique," *Appl. Opt.* **26**, 1603-1606 (1987).
10. M. A. Duguay, Y. Kokubun, and T. L. Koch. "Antiresonant reflecting optical waveguides in SiO<sub>2</sub>-Si multilayer structures," *Appl. Phys. Lett.* **49**, 13–15 (1986).
11. W. J. Wiscombe, G.W. Grams. "The backscattered fraction in two-stream approximations," *J. Atmospheric Sciences* **33**, 2440-2451 (1976).
12. M. Nakazawa. "Rayleigh backscattering theory for single-mode optical fibers," *Opt. Soc. Am.* **73**, 1175-1179 (1983).
13. F. P. Kapron, R.D. Maurer, M. P. Teter "Theory of backscattering effects in waveguides," *Appl. Opt.* **11**, 1352-1356 (1972).
14. A. S. Sudbø, "Why Are Accurate Computations of Mode Fields in Rectangular Dielectric Waveguides Difficult?," *J. Lightwave Technol.* **10**, 418–419 (1992).

---

## 1. Introduction

The minimum reported attenuation for an optical waveguide is about 0.85 dB/m [1], while standard optical fibers show less than 0.2 dB/km for 1550 nm. This discrepancy is usually attributed to scattering due to the presence of imperfections in the core-cladding interface or in

the core itself [2]. In fact, waveguides are built by successive layer deposition, which can not meet the homogeneity achieved by the fiber drawing process, so the number and size of imperfections will really be different in each case. However, there exists such a huge mismatch in the respective attenuations that, in spite of the relative importance of the fabrication processes, it is not obvious that this difference is due to one single cause [3].

Starting from the previous experience in optical waveguide fabrication and simulation in our research group [4,5] and results from similar experiences [6], an optical low coherence reflectometry (OLCR) experiment has been conducted, in order to measure the amount of backscattered light in optical waveguides and compare it to the power expected according to the attenuation observed. This comparison will give an idea of the relative importance of scattering in the losses of integrated waveguides and can serve as an orientation for further studies intending to reduce these losses.

## 2. Optical low coherence reflectometry

The amount of light scattered and guided backwards in an optical waveguide depends on the injected power level  $P(z)$ , the imperfections of the medium (described by the scattering attenuation coefficient,  $\alpha_s$ ) and the guiding characteristics of the waveguide itself (core index, numerical aperture, ...), as scattered light must be guided back to contribute to the reflected power. Thus, power reflected by a length  $dz$  of a waveguide,  $dP_R(z)$ , can be formulated [7] as

$$dP_R(z) = K \cdot P(z) \cdot \alpha_s \cdot dz \quad (1)$$

where  $K$ , the backscattering coefficient, is a constant depending on the waveguide guided mode field distributions (spot size) which indicates the fraction of scattered light which is guided back by the waveguide. The value of  $K$  is in the order of  $10^{-3}$  for a standard optical fiber [7]. This equation is the basic principle of the Optical Time-Domain Reflectometer (OTDR), widely used in optical fiber cables characterization.

If the injected light consists on a pulse of spatial width  $W$ , small enough to assume  $P(z)$  is constant along that length, we can integrate expression (1) to

$$P_R(z) = \frac{\ln 10}{10} \cdot K \cdot P(z) \cdot \alpha_{s_{dB}} \cdot W \quad (2)$$

where  $\alpha_{s_{dB}}$  is the scattering coefficient expressed in dB/m. Therefore, a technique to measure this reflected power would allow us to estimate the value of the scattering coefficient and whether it is or not the origin of waveguide losses.

This technique is Optical Low Coherence Reflectometry (OLCR) [8,9], which uses an interferometer to discriminate the point from where reflected light comes (Fig. 1). Interferometry is based on the superposition of two coherent waves (i.e., with a definite phase relationship). The simplest case, that of two monochromatic waves of intensity  $I_1$  and  $I_2$  out of phase by a time interval  $\tau$ , results in the following expression:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \omega_0 \tau \quad (3)$$

which becomes, in terms of optical path difference (in air)  $\Delta x = \tau \cdot c$  and wavelength  $\lambda_0 = 2\pi c / \omega_0$ ,

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \frac{2\pi}{\lambda_0} \Delta x \quad (4)$$

In practice, the waves will not be strictly monochromatic, and the interference pattern will be limited by the coherence length of the source,  $L_c$ , inversely proportional to its spectral width  $\Delta\lambda$ , in accordance with van Citter-Zernike theorem,

$$L_c \propto \frac{\lambda_0^2}{\Delta\lambda} \quad (5)$$

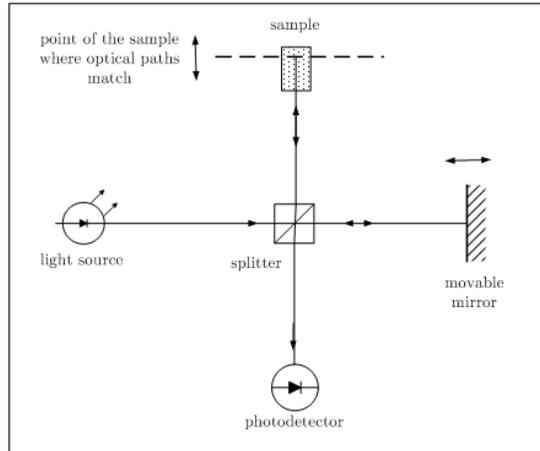


Fig. 1. Basic scheme of the OLCR setup based on Michelson interferometer

By using a low coherence source, only reflected light belonging to the coherence length section interferes and contributes to the detected power. If we now vary the length of one of the arms of the interferometer, the point of the sample which reflects the interfering light changes, allowing us to measure the distributed backscattering by a continuous sweep along the zone under study. The resolution of this technique will be given by the coherence length of the source, and is usually suitable for the analysis of integrated optical waveguides when using a LED, whose spectrum is several nanometers wide, resulting in coherence lengths smaller than the millimeter.

### 3. Experimental setup

The OLCR experiment has been carried out with a Michelson-type interferometer whose arms are optical fibers of similar length, and with an optical 2x2 50/50 coupler in the role of the beam splitter (Fig. 2). The arm formed by the sections (2) and (3) collects the light backscattered by the sample and makes it interfere with a beam obtained directly from the source (Section 4). The exact matching of the lengths of both arms is achieved by means of a step motor with a resolution of 0.08  $\mu\text{m}$ , which allows the examination of the desired point of the sample with great accuracy.

The source used is a superluminescent diode (SLED) Superlum SLD-261-MP-DIL-670, with a central wavelength of 678 nm and a spectral width of 10 nm, resulting in a coherence length of about 46  $\mu\text{m}$ , according to Eq. (5). This result has been confirmed experimentally by measuring the full width at half maximum of the Fresnel reflection at the fiber end. As the length of the waveguides under study will be in the order of the centimeters, the resolution of the interferometer is more than enough. The visible source implies the use of small core (4  $\mu\text{m}$ ) optical fibers, singlemode for those wavelengths.

The interference takes place using a beam splitter cube which redirects both rays to a Si PIN photodetector.

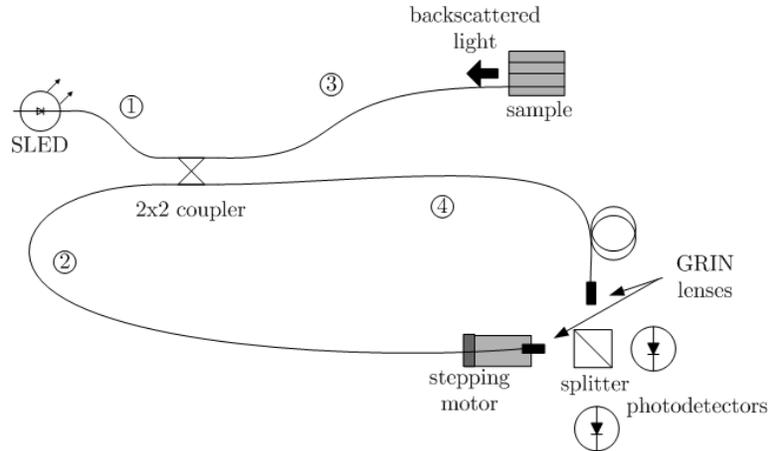


Fig. 2. Final scheme of the OLCR setup.

The main difficulty of this measurement is the difference in power between the two arms of the interferometer, as one of them has an intensity of roughly half the source power, while the other is multiplied by the scattering coefficient of the sample and the coherence length of the source, besides suffering a second pass by the 50/50 coupler. The expected ratio between the two beams is expected to be less than  $1:10^5$ , whereas the optimum ratio, which produces the maximum contrast according to Eq. (4), is 1:1, as the term  $2\sqrt{I_1 I_2}$  gives the amplitude of the interference pattern. To overcome this complication, the optical path is varied sinusoidally with the introduction of a piezoelectric crystal behind the fiber end holder, generating a harmonic signal at the detector and making possible synchronous detection using a lock-in amplifier, with the subsequent improvement of the signal to noise ratio. In fact, there is a simultaneous measurement of the first two harmonics of the signal to achieve a stable result.

Finally, a second detector has been placed on the other side of the beam splitter cube. The signal in this second detector is 180 degrees out of phase with that of the first one, so the difference of the two signals will allow us to double the signal to noise ratio. With all these modifications, the sensitivity of our system is about 95dB under the input signal.

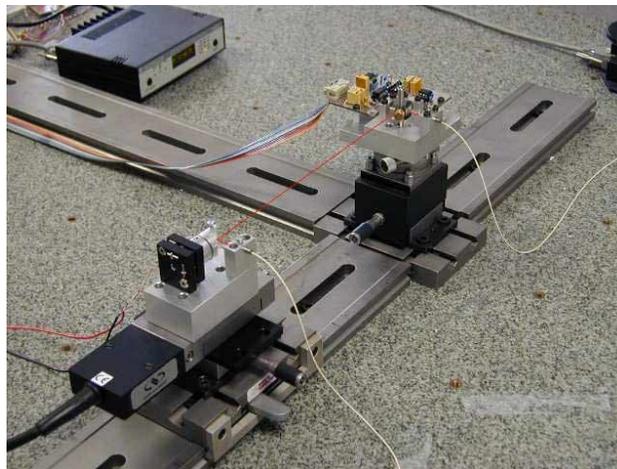


Fig. 3. OLCR experimental setup (light ray has been simulated).

#### 4. Measurements

The setup described in the previous section has been used to measure the backscattering of a series of straight rib ARROW (AntiResonant Reflecting Optical Waveguide) silica-on-silicon waveguides fabricated by our research group. These waveguides achieve the confinement of the light by means of a constructive reflection produced by a multilayer instead of the total internal reflection (TIR) of conventional optical waveguides [10]. However, our waveguides (see Fig. 4) present antiresonant reflection only in the core-substrate interface, while the other three interfaces use TIR. The optimum operation wavelength for these devices is around 670 nm.

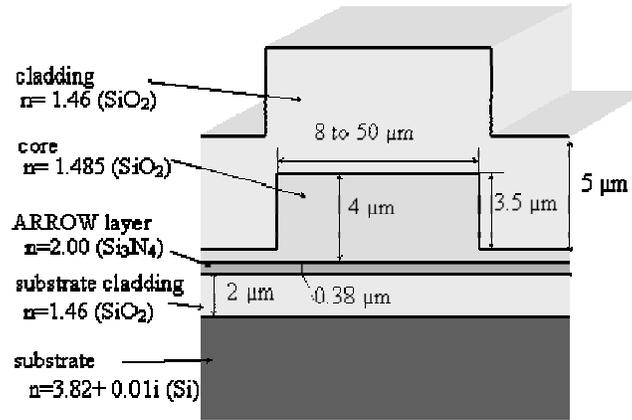


Fig. 4. Section of the ARROW waveguides fabricated.

The substrate cladding  $\text{SiO}_2$  layer was made by thermal oxidation of the silicon substrate, obtaining a refractive index of about 1.46. Silicon nitride and silicon dioxide core layers were deposited using LPCVD at 800 °C and PECVD at 300 °C respectively, which are CMOS compatible deposition processes. Rib walls were performed by dry reactive ion etching (RIE), and finally a cladding layer was deposited using PECVD.

As stated before, attenuation losses of integrated optics waveguides are substantially higher than those of optical fibers. For the ARROW waveguides under study, typical measured losses are about 30 dB/m at 670 nm, while a standard optical fiber presents only  $3 \cdot 10^{-3}$  dB/m at that wavelength. For this difference to be attributed to small variations of the core refractive index, which result in isotropic Rayleigh scattering, the backscattering measured in the ARROW waveguides should be higher than those of the fibers in this same proportion.

Specifically, according to (2), the reflectivity  $R(z)$  of the waveguide is:

$$R(z) = 10 \log \left( \frac{P_R(z)}{P(z)} \right) = 10 \log [0.23 \cdot K \cdot \alpha_{sdb}(z) \cdot W] \quad (6)$$

If losses are due to scattering, the scattering coefficient  $\alpha_{sdb}$  should almost equal  $\alpha_{db}$ , the total attenuation coefficient, which is also supposed  $z$ -independent. As the coherence length of the source is  $W=45 \mu\text{m}$  and with  $K \approx 10^{-3}$  as in an optical fiber, we can obtain:

$$R_{\text{waveguide}} = 10 \log [0.23 \text{dB}^{-1} \cdot 10^{-3} \cdot 30 \text{dB} / \text{m} \cdot 4.5 \cdot 10^{-5} \text{m}] = -65 \text{dB}$$

$$R_{\text{fiber}} = 10 \log [0.23 \text{dB}^{-1} \cdot 10^{-3} \cdot 3 \cdot 10^{-3} \text{dB} / \text{m} \cdot 4.5 \cdot 10^{-5} \text{m}] = -105 \text{dB}$$

On the other hand, if the scattering in integrated optical waveguides is produced by large size defects (resulting in anisotropic scattering [11]), or if the difference is caused by an

increase of the absorption or a defective light confinement, the backscattered light fraction should not be much larger than in the optical fiber measurement, as the term  $\alpha_s$  would be similar in both cases, and the only difference would be the  $K$  parameter.

The reflectivity of the samples is estimated using the Fresnel reflection in the interface between a fiber optic and the air (-14.7 dB) as a reference. It is also necessary to take into account the insertion losses at the sample, which result in a measured reflectivity slightly smaller than its real value.

Several measurements of the initial and final sections of different waveguides were made in order to obtain their reflectivity. The main results are exposed below.

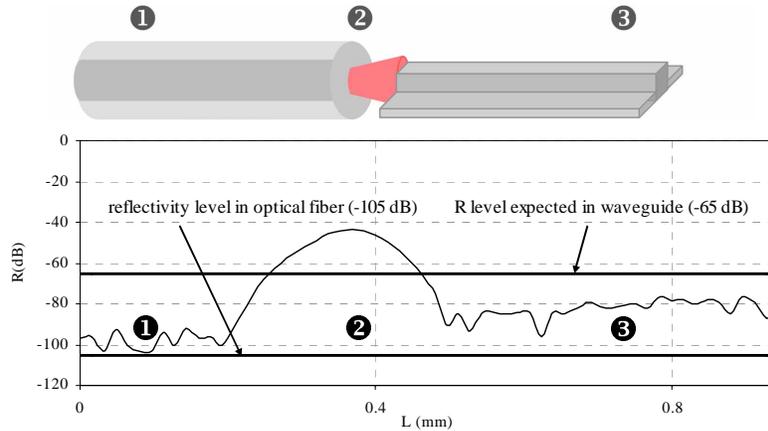


Fig. 5. Reflectivity of the input fiber and the initial section of an 8  $\mu\text{m}$  wide waveguide

Figure 5 shows the reflectivity at the input fiber end and at the initial section of an ARROW waveguide. Rayleigh scattered light in the optical fiber (section 1) can not be detected, as its level (-105 dB) is under the -95dB sensitivity of our system. On the other hand, the reflectivity at the waveguide region (3) is near -80dB. Note that the reflection peaks at the interfaces fiber-air and air-waveguide, now fused in one only peak, are much lower than the -14.7 dB expected, due to the utilization of an index liquid of 1.45 to avoid high reflection coefficients which would make impossible the observation of Rayleigh scattering in these sections.

Figure 6 shows the final section of a 10  $\mu\text{m}$  wide waveguide (1) and the following air region (3). The reflection at this end of the waveguide is around -20dB, due to the insertion losses and to the fact that the surface is not as perfect as that of a cleaved fiber. This second measurement confirms that the fiber backscattering is under the noise level, as the signal at the air region is the same (-95dB, the noise level) than at the optical fiber of figure 5.

The backscattering level of the ARROW waveguides is again about -80dB, as the waveguide length is 2.5 cm and total losses (at 0.3 dB/cm) of 0.7 dB can be neglected.

Both measurements show an appreciable increase of the backscattered light in ARROW waveguides compared to that of the optical fiber. However, that reflectivity of around -80dB would represent an attenuation due to isotropic Rayleigh scattering of only 0.01 dB/cm, so some other factors must exist to justify the 0.3 dB/cm observed.

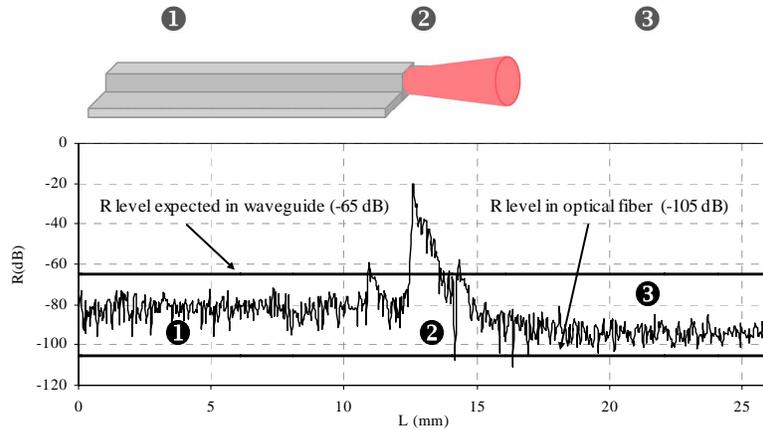


Fig. 6. Reflectivity of the end section of a 10  $\mu\text{m}$  wide waveguide

One possible explanation is that the backscattering coefficient  $K$  of Eq. (6) has a much lower value in the integrated waveguide than in the optical fiber (around  $10^{-5}$  vs.  $10^{-3}$  for the fiber). As this parameter represents the ratio between guided backwards scattering and total scattering, it is usually related to the waveguide numerical aperture [12,13] or spot size [7], which are expected to be in the same order of magnitude in a 4  $\mu\text{m}$  singlemode fiber and in the measured ARROW waveguides. An experimental evidence for this are the low insertion losses, around 0.5 dB, measured at the fiber to waveguide fire coupling. Although there must be some differences between cylindrical and rectangular geometries, the fact that losses due to field matching between these two waveguides are low implies that  $K$  parameter of the ARROW waveguides should be in the order of that in the optical fiber.

Moreover, the glancing angle of ARROW waveguides calculated according to [10] is very similar to that produced at the interface between two media with the refractive indices of the core and cladding of a singlemode fiber. This reinforces our statement that the  $K$  parameter of the fiber should be similar to that of the measured waveguides.

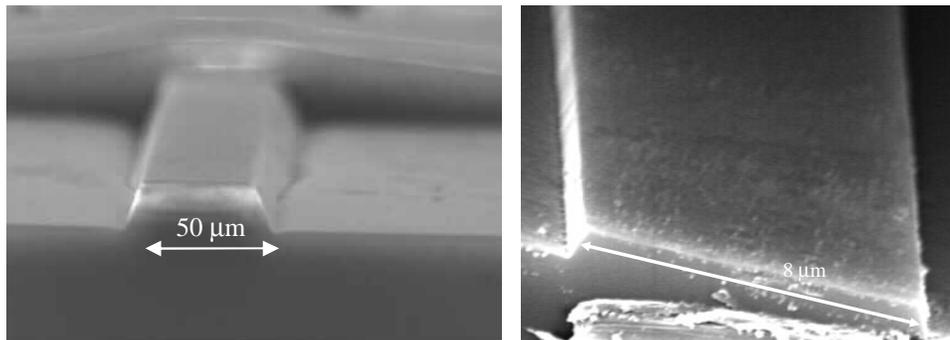


Fig. 7. Images of the fabricated ARROW waveguides without the upper cladding layer.

Another possibility is the existence of anisotropy in the scattering, which would also modify the value of  $K$ , resulting in a decrease of the fraction of light scattered backwards and, as a consequence, of the measured reflectivity. For such an anisotropy to exist, the size of the scatterers should be larger than the operating wavelength (678 nm), the condition for Mie scattering to dominate over Rayleigh scattering [6,11]. However, microscope images of the fabricated waveguides (Fig. 7) show the nonexistence of such large defects in the required concentration.

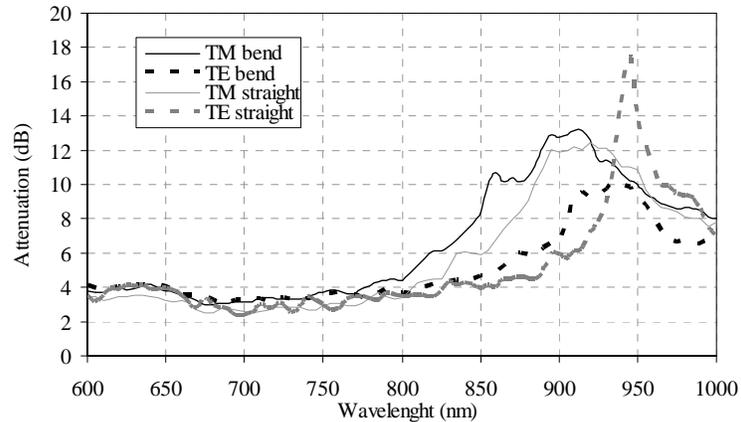


Fig. 8. Measured dependence on wavelength of the attenuation of ARROW waveguides

Another possibility is a contribution to scattering at the sidewalls of the rib waveguides, due to surface roughness. In our opinion, it is hardly assumable that it is the main contribution to attenuation of low loss, low index contrast, wide integrated waveguides: despite from the fact that light should be mainly forward scattered, propagation losses should be wavelength dependent and decrease when waveguide width or rib etching depth increases. In [4] we found that none of these dependences was measured in ARROW waveguides similar to the ones presented in this work.

Finally, the hypothesis of power absorption in the substrate under the ARROW layers as the origin of the increase in attenuation can be neglected as well, because the calculated reflectivity of those layers is enough to achieve losses under 0.5 dB/m. The experimental characterization of the waveguides (Fig. 8) shows the operating wavelength (678 nm) is in the minimum attenuation (and higher reflectivity) region. Moreover, a bad design of the ARROW layers would result in different attenuation for TE and TM modes, as antiresonant reflection is polarization dependent, difference which does not exist in the region of interest. Also, the same discrepancies between losses and backscattering have been observed by other authors for TIR waveguides [6].

Thus, another explanation should be proposed. One possibility is that, due to the rectangular geometry of the waveguides, a perfect matching of the electromagnetic fields into the waveguide is not possible [14], leading to the absence of strictly guided modes, which are invariant along the propagation direction. This may result in partial coupling of the fields with radiation modes and the introduction of a new attenuation factor which does not contribute to backscattering, as light is mainly forward radiated.

Our results are reinforced by those of [6], where Takada et al. measure the backscattering of a 1.7 dB/m attenuation integrated optical waveguide. This attenuation should correspond to a reflectivity due to Rayleigh isotropic scattering 39 dB above that of the optical fiber, but both backscattering measurements are almost identical at -105 dB. These results (see table 1) match those of our experiment and favor the hypothesis that the main attenuation factor in integrated optical waveguides is not scattering.

Note that the reflectivity  $R$  expected is very similar in both experiments although the attenuation of the waveguides is very dissimilar, due to the differences in central wavelength and spectral width of the light sources employed, which compensates the effect of the attenuation.

Also, the reflectivity measured in our experiment is closer to the reflectivity expected than in Takada's experiment. This implies that, in our case, part of the attenuation is in fact scattering attributable, whereas Takada's waveguides, due to a lower concentration of defects,

show much lower scattering. However, in both cases there exists an important fraction of losses which can not be explained only with scattering phenomena.

Table 1. Summary of the reflectivity measurements in optical fibers and integrated waveguides

	This experiment	Takada et al.
R expected fiber	-105 dB	-105 dB
R measured fiber	<-95 dB	-105 dB
R expected waveguide	-65 dB	-66 dB
R measured waveguide	-80 dB	-105 dB
Scattering attributable attenuation	1 dB/m	$2 \cdot 10^{-4}$ dB/m
Non-scattering attenuation	29 dB/m	1.6998 dB/m

## 5. Conclusions

An OLCR setup has been developed in order to measure backscattering in optical waveguides. The results show that the amount of backscattered light is much lower than the necessary to explain the attenuation of the waveguides, which must then be attributed to other factors, as the inexistence of perfectly guided modes.

## Acknowledgments

The authors thank the Spanish Ministerio de Ciencia y Tecnología (through project DPI2003-09735-C02-02) for financial support of the present work.