Parameters Affecting Bending Losses in Graded-Index Polymer Optical Fibers

J. Arrue, J. Zubia, G. Durana, and J. Mateo

***Abstract*—Radiation losses that occur when bending graded-index polymer optical fibers (POFs) are analyzed as a function of the profile exponent, the light wavelength, the fiber core radius, and the length of the bent section. For this purpose, a ray-tracing model is used, which combines both the generalized Fresnel power transmission coefficients for curved graded-index media and the differential equations that govern the ray paths in highly multimode graded-index fibers. This model is applied to the most recent types of graded-index POF, for which the choice of the core radius and profile exponent is discussed from the point of view of bending losses (the greater the profile exponent and the core radius, the greater the bending losses). The influence of profile exponents different from two is included for the first time.**

***Index Terms*—Bending loss, graded-index polymer optical fiber (GI POF), graded refractive-index profile.**

I. Introduction

COMPARED with glass fibers, one of the most important features of polymer optical fibers (POFs) is the possibility of adopting a large core diameter, thus allowing low installation and handling cost [1]. Therefore, POFs are usually very advantageous for short optical links requiring a large number of splices to interconnect multiple nearby devices, like in buildings or vehicles. In such applications, the fiber is often bent with bend radii small enough for significant radiation losses to occur [2]. While POFs are very flexible, the bend radius is limited by the maximum permissible light power attenuation in the bend due to radiation losses. In addition, nowadays high-bandwidth graded-index (GI) POFs are commercially available, which tend to exhibit much higher bending losses. Specifically, a graded core having the same radius and twice the index difference of the homogeneous core will show a similar performance in bends [3].

On the other hand, losses also increase when increasing either the core radius or the value of the profile exponent or the light wavelength, although in different proportions, respectively. For example, if the core radius were twice as large, the bend radius would also have to be doubled to obtain approximately the same radiation losses. In other words, the results are scalable, except for the fact that the light wavelength has a small influence on radiation losses, which can be neglected for large core radii. In this context, the choice of a core radius as small as 65 μm for the new PF polymer base GI POF called "Lucina" is beneficial from the point of view of reducing bending losses, although its relatively small numerical aperture has the opposite effect. Another commercially available GI POF is that made of polymethylmethacrylate (PMMA), whose higher numerical aperture allows greater core radii for the same losses.

In this paper, the influence on bending losses of hypothetical variations in the parameters of commercial GI POF is discussed. In addition, the results presented are intended to clarify what parameters affect bending losses in graded-index POF and to what extent. Since the analysis has been mostly theoretical, the method for computing bending losses in graded-index fibers is also explained, which takes into account both tunneling rays and different profile exponents.

Theoretical results for bending losses can be obtained by using a ray-tracing method, which combines the ray paths of geometric optics and the generalized Fresnel power transmission coefficients for curved graded-index media. The ray-tracing method serves to obtain the total output power in the absence of material absorption by considering the radiation losses experienced by the individual light rays at each reflection or turning point [4]. In the case of graded-index POF, rays that propagate inside the core will be lost if they reach the core-cladding interface, so radiation losses will be greater than those obtained for step-index POF [5]. In addition, a ray can lose a significant amount of power even if it does not enter the cladding, due to tunneling losses in bends. The total light power entering and exiting the POF is the sum of the powers of all the rays at the input and output ends, respectively.

Bend loss has been subject of detailed studies, both for telecommunications and for sensing applications [5]–[9]. However, a complete theoretical calculation of bending losses in POF of any refractive index profile is presented here for the first time. The most original contribution is the inclusion of a simple method that allows one to calculate ray paths when the profile exponent is different from two.

II. Power Transmission Coefficients for Curved Graded-Index Media

When rays in graded-index fibers travel along bends, there are radiation losses, which are either by refraction or by tunneling. The graded profile tends to concentrate the light along the axis, but any ray that reaches the interface is lost by refraction [9]–[12]. Since the core and cladding refractive indexes coincide at the interface, the transmission coefficient is $T \approx 1$ for refracting rays. On the other hand, the transmission coefficient is generally small for the rest of the rays, which are tunneling [4]. These rays disappear in the core at the turning point at a distance d from the interface and reappear in the cladding at a finite distance beyond the interface. The transmission factor for

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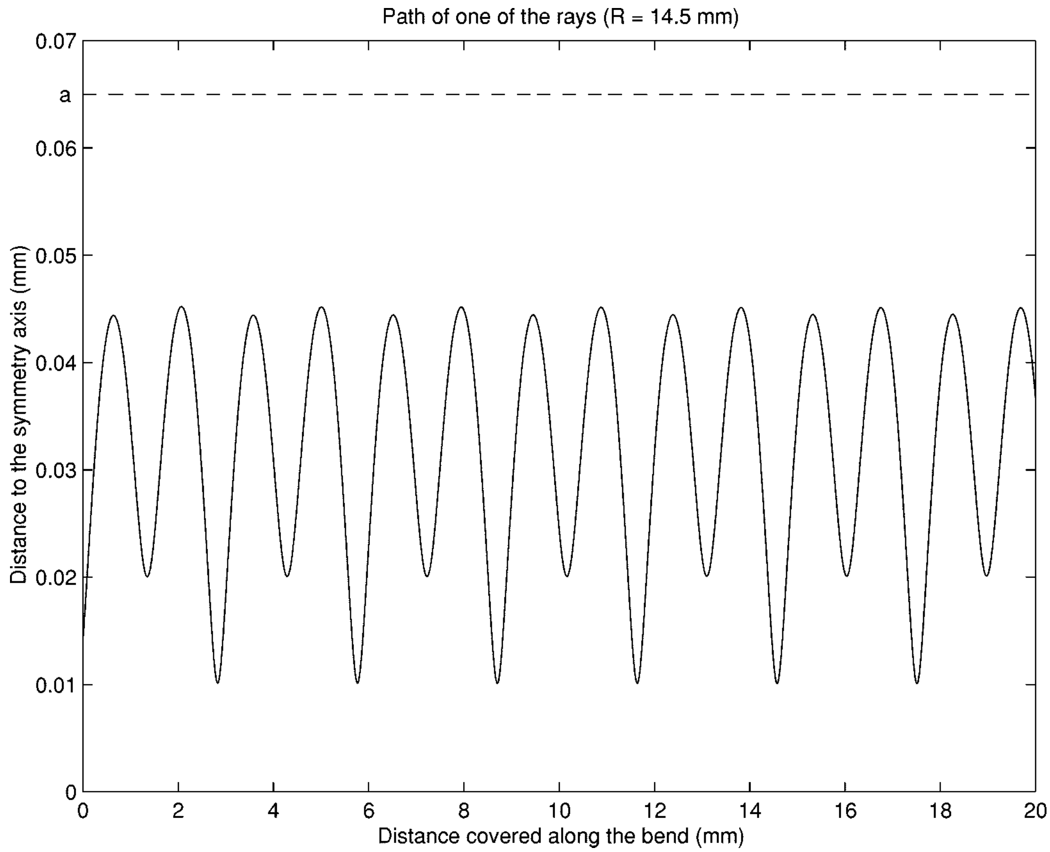

Fig. 1. The path of one of the numerous rays considered to study the radiation losses for a bend radius of 14.5 mm, in the case of profile exponent equal to two, core radius of 0.065 mm, and core and cladding refractive indexes equal to 1.353 and 1.340, respectively. For this ray, $\beta = 1.3482$ and $l = 0.1179$.

tunneling rays depends on the radius of curvature ρ_c of the surface of constant refractive index at the turning point, measured in the plane of the ray in the proximity of such a point. It is given by [11]

$$T = \frac{4}{\pi^2}\,\frac{\kappa}{\{a + b\kappa + c\kappa^2\}} \tag{1}$$

where

$$\begin{aligned} a &= \{Ai(v)^2 + Bi(v)^2\}\,\{Ai'(u)^2 + Bi'(u)^2\} \\ b &= \frac{2}{\pi^2} + 2\{Ai(u)Ai'(u) + Bi(u)Bi'(u)\} \\ &\quad\cdot \{Ai(v)Ai'(v) + Bi(v)Bi'(v)\} \\ c &= \{Ai(u)^2 + Bi(u)^2\}\,\{Ai'(v)^2 + Bi'(v)^2\} \\ \kappa &= \left\{\frac{\rho_c\theta_c(0)^2}{2\,d} - 1\right\}^{-1/3}. \end{aligned} \tag{2}$$

Ai and Bi are Airy functions of the first and second kinds, respectively, with arguments

$$\begin{aligned} u &= \kappa^{-1}\,d\left[\frac{k^2 n(0)^2 2}{\rho_c}\right]^{1/3} \\ v &= -\left(\frac{k\rho_c n(0)}{2}\right)^{2/3}\left\{2\,\frac{d}{\rho_c} - \theta_c^2(0)\right\} = \kappa^{-2}u. \end{aligned} \tag{3}$$

The wavenumber is

$$k = 2\pi/\lambda_0 \tag{4}$$

where λ_0 is the free-space wavelength.

The local critical angle $\theta_c(0)$ is defined by

$$\theta_c(0) \cong \sin\theta_c(0) = \left\{1 - \frac{n_2^2}{n^2(0)}\right\}^{1/2} \tag{5}$$

where $n(0)$ is the refractive index at the turning point and n_2 is the cladding refractive index. The above expressions correspond to a continuous refractive index profile $n(y)$ decreasing monotonically through the turning point $y = 0$ to the interface $y = d$, y being the radial distance to the turning-point caustic [4].

III. Ray Paths for Parabolic Index Fibers

Let us now consider a refractive index profile that can be put in a separable form, i.e.,

$$n^2(\rho, z) = n_1^2(\rho) + n_2^2(z). \tag{6}$$

It can be shown that for a separable profile given by the above equation, it is possible to derive equations, simple integrations of which would give the exact ray paths [10]. Obviously, a parabolic index fiber has a separable profile

$$n^2(\rho, z) = n_0^2[1 - 2\Delta(\rho^2 + z^2)/a^2] = n_0^2 - g\rho^2 - gz^2 \tag{7}$$

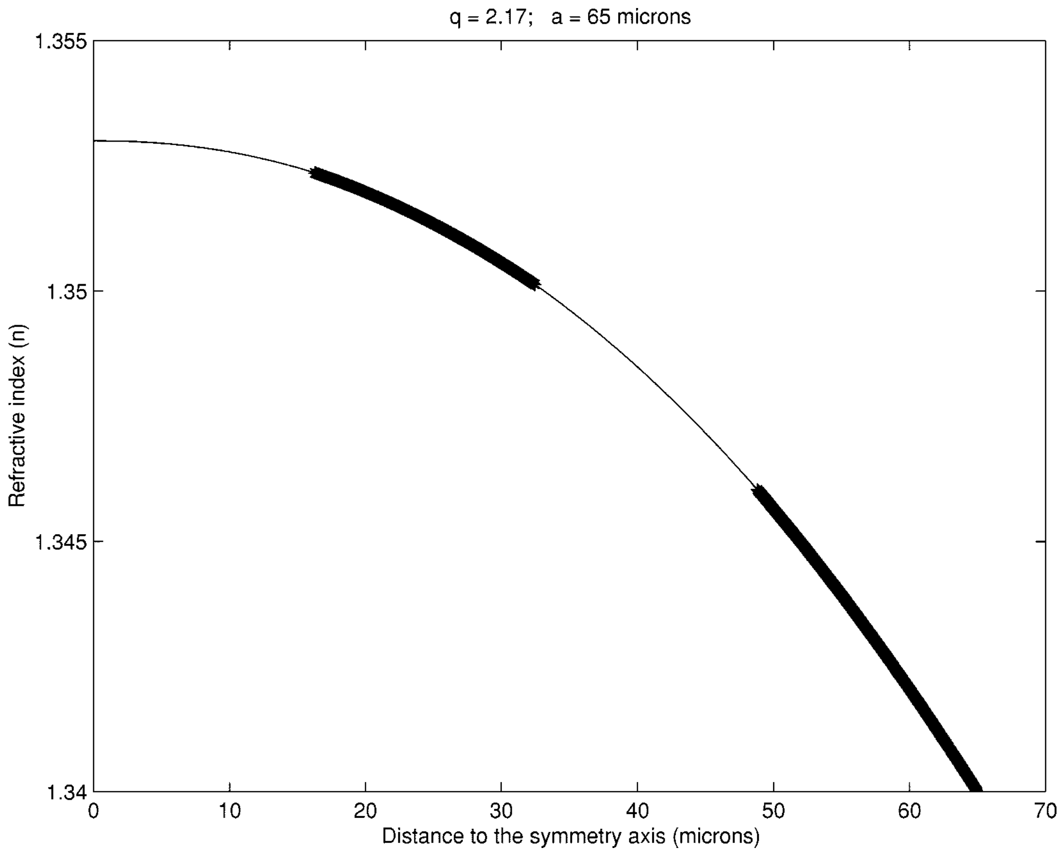

Fig. 2. Four parabolas of the form "$a + cu^2$" can fit the core refractive index very approximately when the profile exponent q is different from two ($q = 2.17$ in the figure). The exact refractive index has been plotted with a thin line and the second and fourth parabolas has been plotted with thick lines.

where n_0 is the refractive index at the fiber symmetry axis, a is the core radius, Δ is the relative difference of refractive indexes, $g = 2\Delta(n_0^2/a^2)$, ρ is the projection onto the meridional plane of the radial distance to the center of the fiber core, and z is the component of such a distance along the perpendicular axis, so the distance squared is $(\rho^2 + z^2)$.

It is straightforward from (6) and (7) that we can take

$$n_1^2(\rho) = n_0^2 - g\rho^2 \tag{8}$$

$$n_2^2(z) = -gz^2. \tag{9}$$

The exact ray paths in a circularly bent graded-index POF can be obtained from [10]

$$\begin{aligned} \frac{d^2\rho}{d\xi^2} &= 2\left[\frac{n_1^2(\rho) - \tilde{l}^2}{\tilde{\beta}^2}\right]\left(1 + \frac{\rho}{R}\right)^3 \frac{1}{R} \\ &\quad + \frac{1}{2\tilde{\beta}^2}\left(1 + \frac{\rho}{R}\right)^4 \frac{dn_1^2(\rho)}{d\rho} - \left(1 + \frac{\rho}{R}\right)\frac{1}{R} \end{aligned} \tag{10}$$

$$\begin{aligned} \frac{d^2 z}{d\xi^2} &= 2\left(\frac{dz}{d\xi}\right)\left(\frac{d\rho}{d\xi}\right)\left(1 + \frac{\rho}{R}\right)^{-1} \frac{1}{R} \\ &\quad + \frac{1}{2\tilde{\beta}^2}\left(1 + \frac{\rho}{R}\right)^4 \frac{dn_2^2(z)}{dz} \end{aligned} \tag{11}$$

where ξ is the distance measured along the fiber symmetry axis, R is the bend radius, and l and β are two ray invariants, which can be obtained from the angle θ_z with the z-direction and the angle θ_ξ with the tangent to the fiber symmetry axis by using

$$\begin{aligned} 1^2 &= (n\cos\theta_z)^2 - n_2(z)^2 \\ \beta &= n[(R+\rho)/R]\cos\theta_\xi. \end{aligned} \tag{12}$$

The exact ray paths can be obtained by solving the two simultaneous differential equations given above. For the analysis to be correct, we need to consider a sufficiently high number of rays at the entrance of the bent section. If a ray path separates from the fiber symmetry axis more than the core radius, we need not go on with the calculation of the corresponding path, since all the power is lost by refraction at the interface. If, on the contrary, a ray path has remained at any time within the core during a sufficiently high number of oscillations, then it will not be lost by refraction, since the shape of the ray path repeats itself periodically (Fig. 1). However, even when all the refracting rays have disappeared, tunneling rays will cause the radiation loss to increase with the distance covered. In fact, any ray in a bent optical fiber is leaky and will lose power along the bend. The theory of the transmission coefficients allows one to calculate the power loss by assuming that a ray will only lose power at the turning points, by means of the tunneling mechanism, or at the interface, by refraction.

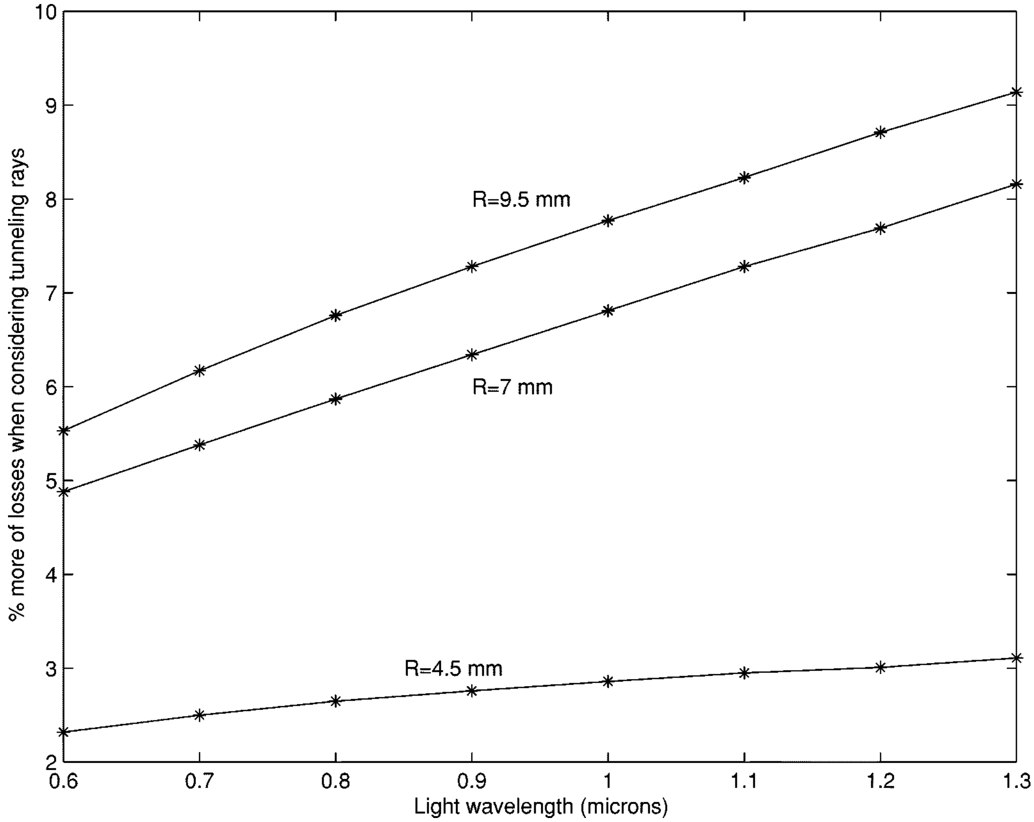

Fig. 3. Percentage of additional losses that would be obtained with the "Lucina" fiber ($a = 65\ \mu$m) when considering tunneling rays for 1-1/4 turns and different bend radii as a function of the light wavelength.

IV. Ray Paths for Profile Exponents Different From Two

If the refractive index profile q is not exactly equal to two, then (7) cannot be applied. The new equation is

$$n^2(\rho, z) = n_0^2[1 - (2\Delta/a^q)(\rho^2 + z^2)^{q/2}]. \tag{13}$$

Now we cannot separate (13) as $n_1^2(\rho) + n_2^2(z)$ in an exact manner. However, we can still use the differential equations (10) and (11) if we divide the core in several concentric zones, each of them fitting a parabolic refractive index profile very approximately. The more zones we consider, the better the approximation is, although the required computation time increases as well. For this paper, four different concentric zones have been considered. Specifically, if we name the radial distance to the fiber symmetry axis u, then the four following parabolas that can be put in a separable form as in (6) were considered:

$$\begin{aligned} S_0(u) &= a_0 + c_0 u^2 && 0 \le u \le a/4 \\ S_1(u) &= a_1 + c_1 u^2 && a/4 \le u \le a/2 \\ S_2(u) &= a_2 + c_2 u^2 && a/2 \le u \le 3a/4 \\ S_3(u) &= a_3 + c_3 u^2 && 3a/4 \le u \le a \end{aligned} \tag{14}$$

where a_0, c_0, a_1, c_1, a_2, c_2, a_3, and c_3 are constants that can be determined by obliging any two contiguous parabolas to yield the same value at the limit between the two contiguous zones. The results obtained for $q = 2.17$ are shown in Fig. 2, together with the curve of the exact refractive index.

Bandwidth characteristics of the GI POF have already been estimated theoretically as a function of the index exponent q [13]–[16]. From the point of view of bandwidth, the optimum index exponent value is located around $q = 2.3$ in the case of the PMMA base POF, and around $q = 2.17$ in the case of the PF polymer base POF. In this paper, we analyze these and other index exponents as well, but from the point of view of bending losses.

V. Ray Distribution at the Entrance of the Bent Section

Once the ray propagation model in a bent optical fiber has been established, it is necessary to know the amount of power associated with each ray at the entrance to the bent section. Equivalently, we can consider that all rays entering the bend transport identical power if we take the number of rays to be proportional to the corresponding density of optical power per unit cross-sectional area. To calculate this density, we can analyze a differential element of area of the fiber cross-section. The differential element of solid angle associated to the rays passing through this element of area is

$$d\Gamma = \text{sen}\theta_\xi \cdot d\theta_\xi \cdot d\theta_\phi \tag{15}$$

where θ_ξ and θ_ϕ are the angle with the fiber symmetry axis and the azimuthal angle, respectively. If we only consider those rays that propagate without radiation losses when the optical fiber is straight, then $\theta_\xi \le \theta_c$ (θ_c being the complementary critical

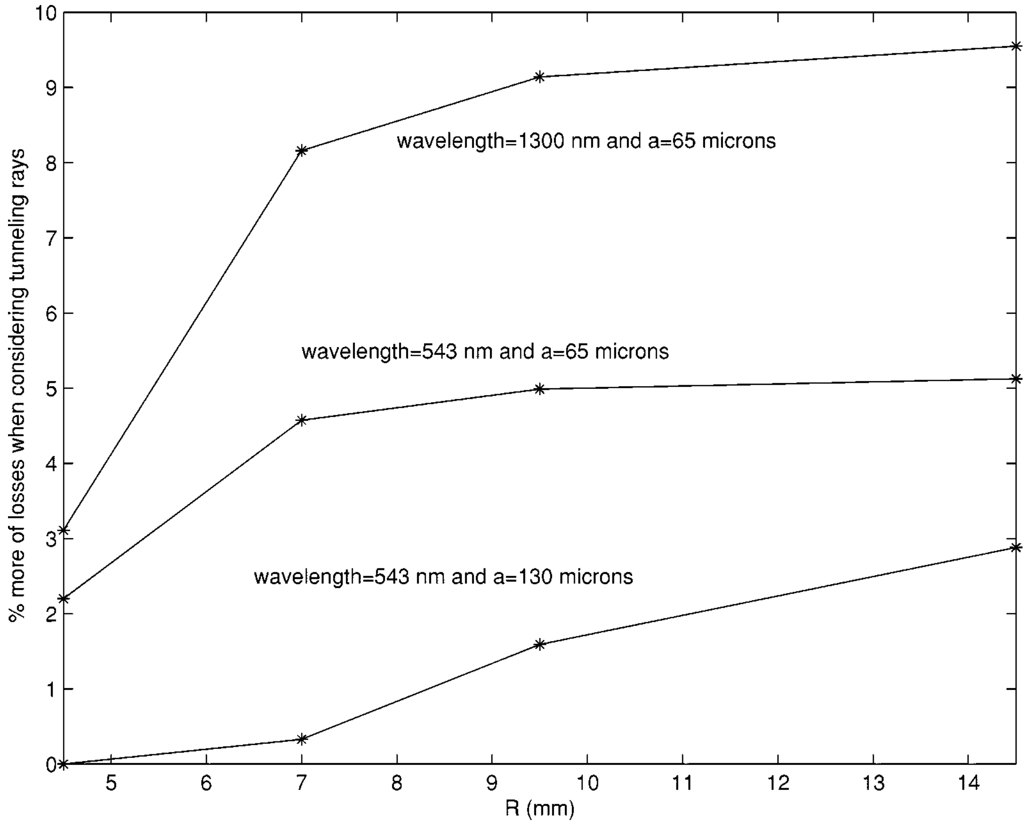

Fig. 4. Combined influence of the light wavelength and the fiber core radius a on the "Lucina" fiber as a function of the bend radius for 1-1/4 turns.

angle at that element of area). After having defined the differential element of solid angle, a certain amount of power must be assigned to it. Often the light source utilized with POF is a light-emitting diode, which can be approximated by a *Lambertian* light source, so the element of power dP per unit area radiated into solid angle $d\Gamma$ is given by

$$dP/dA = I_0 \cdot \cos\theta_\xi \cdot d\Gamma \tag{16}$$

where I_0 is the maximum luminous radiance. Thus, the total power per unit cross-sectional area after a sufficiently long straight section of fiber is calculated by integrating over the ranges of variation of all the angles, with $\theta_\xi \le \theta_c$. The result obtained is

$$dP/dA = K(n^2 - n_{\text{cl}}^2) \tag{17}$$

where K is a constant and n_{cl} is the cladding refractive index.

According to (17), there are more bound rays at the center than in the proximity of the core-cladding interface. Now if we take into account (7), we obtain

$$dP/dA \propto \{1 - (u/a)^q\} = 1 - x^q \tag{18}$$

where $x = u/a$. Therefore, the distribution of rays is chosen to satisfy that more rays should enter the bend at small distances u, in such a way that the contour of the histogram of the number of rays varies as $1-x^q$.

VI. Simulation Results

For the analysis, a computer program has been prepared by using the software Matlab. Our program makes use of the formulas explained in the above sections. Specifically, about 10 000 rays have been considered at the entrance of the bend, distributed as explained in Section V. The choice of this number is based on a comparison between the differences in the results obtained for several numbers of rays. For example, in principle, 100 000 rays would be more exact, but the results obtained with 10 000 rays were nearly the same and the computation time about ten times shorter (for example, for $q = 1.8$ and $R = 7$ mm, a relative output power of 0.2067 was obtained for 10^4 rays and 0.1943 for 10^5 rays).

Since the analysis is computational, any set of physical parameters such as core and cladding refractive indexes could be chosen, but we have considered it convenient to take the values of available GI POF. Regarding the simulated profile exponents, a range of values in the proximity of two was chosen, since this is the only range that makes sense from the point of view of compensating modal dispersion. The two GI POFs that we have had in mind for the choice of the physical parameters have been the PMMA base POF, whose core and cladding refractive indexes are $n_0 = 1.512$ and $n_r = 1.492$ ($n_o = 1.507$ in the case of the low numerical aperture ones), and the PF polymer base POF called "Lucina," whose respective indexes are $n_0 = 1.353$ and $n_r = 1.340$. To be able to compare the theoretical results with our experimental measures, in the latter case the core radius was chosen to be 65 μm. In addition, to illustrate the difference between a GI POF and a step-index POF, we have compared the

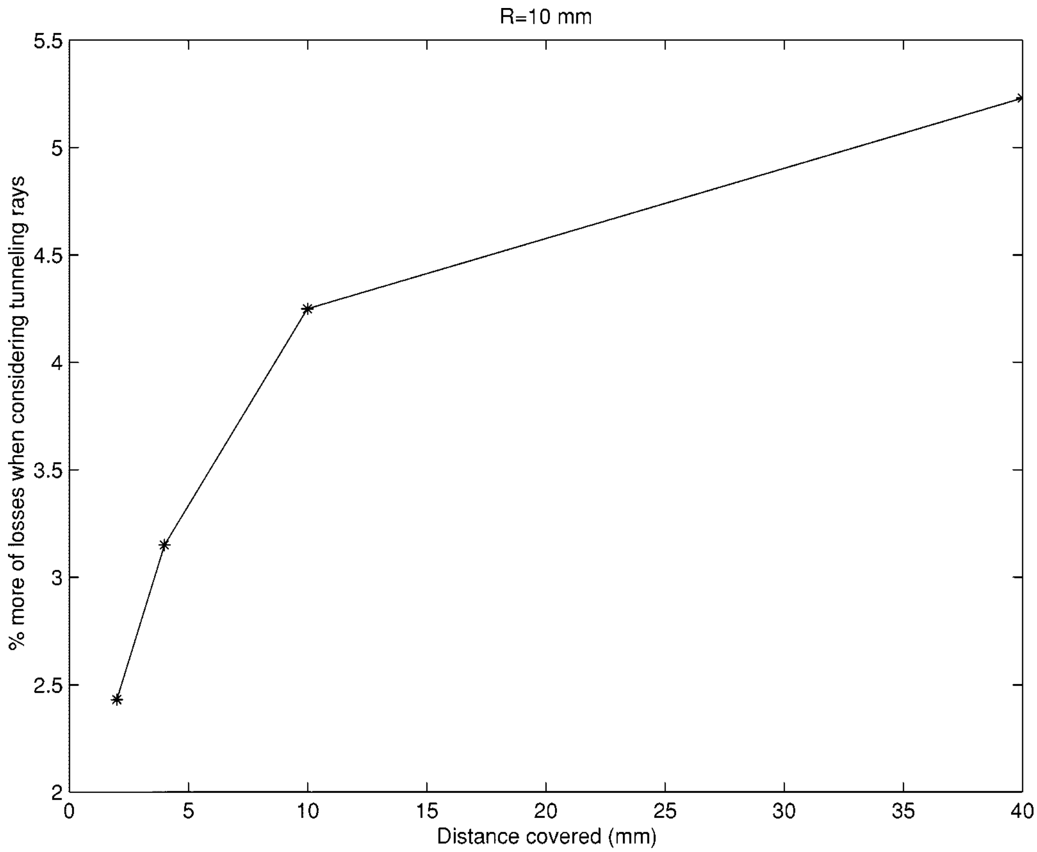

Fig. 5. Percentage of additional losses that would be obtained with the "Lucina" fiber (Lucina LGR01AO1OL) when considering tunneling rays as a function of the distance covered around a cylinder of fixed bend radius (10 mm).

experimental results obtained for a typical step-index PMMA POF (1 mm core diameter, $n_o = 1.492$, $n_r = 1.417$) with the theoretical results for a 1-mm-core GI PMMA POF.

Another parameter to choose was the length of the bend or, equivalently, the number of turns around a cylinder of the desired bend radius. We could see that refracting rays disappear very rapidly, since the oscillations of the ray path are very fast (Fig. 1), and also that tunneling rays lose their power much more slowly, due to the much smaller transmission coefficients. For example, very small output power differences were obtained for 1/4 of a turn and for 1-1/4 turns for a bend radius of 7 mm, because, in this case, refracting rays lose all of their power in less than one-quarter of a turn. Since our experimental curve for the Lucina fiber was obtained with 1-1/4 turns, most of the graphs presented here correspond to this number of turns.

The results presented in this paper yield the ratio of the output power to the input power ($Pout/Pin$) in different cases, so as to analyze the different influences of the parameters.

A. Influence of Tunneling Rays

To be able to isolate the losses due to tunneling rays from those due to refracting rays, we calculated both the total radiation losses and the losses that would be obtained if the transmission coefficient of tunneling rays were always neglected. The difference between the two values yields the desired contribution of tunneling rays. This result is interesting because tunneling rays are the only ones whose radiation losses depend on wavelength. We obtained that the influence of wavelength on the total radiation losses is small. This contribution decreases as the wavelength decreases in relation to the core radius—for example, if we augment the core radius while maintaining the light wavelength fixed. For this reason, for large core radii (e.g., 0.5 mm) and typical wavelengths (e.g., in the range between 0.6 and 1.3 μm), the influence of wavelength is negligible. For smaller core radii (e.g., 65 μm in the case of the Lucina fiber), the ratio of output power to input power is lower than one, mainly due to refracting rays, but to a certain extent, due to tunneling rays as well.

In Fig. 3, we show the percentage of additional losses that would be obtained with the Lucina fiber when considering tunneling rays for 1-1/4 turns and different bend radii as a function of the light wavelength. We can observe that as the bend radius decreases, refracting losses grow faster than tunneling ones.

In Fig. 4, we analyze the combined influence of the light wavelength and the fiber core radius a on the "Lucina" fiber as a function of the bend radius for 1-1/4 turns. We can see that all three curves tend to stabilize at a constant value for large bend radii, since this implies sufficiently long distances for the most leaky tunneling rays to disappear. However, the additional losses due to tunneling rays are higher for longer wavelengths (compare the two uppermost curves) and for smaller core radii (compare the two lower curves).

In Fig. 5, we have plotted the percentage of additional losses that would be obtained with the "Lucina" fiber when considering tunneling rays as a function of the distance covered around

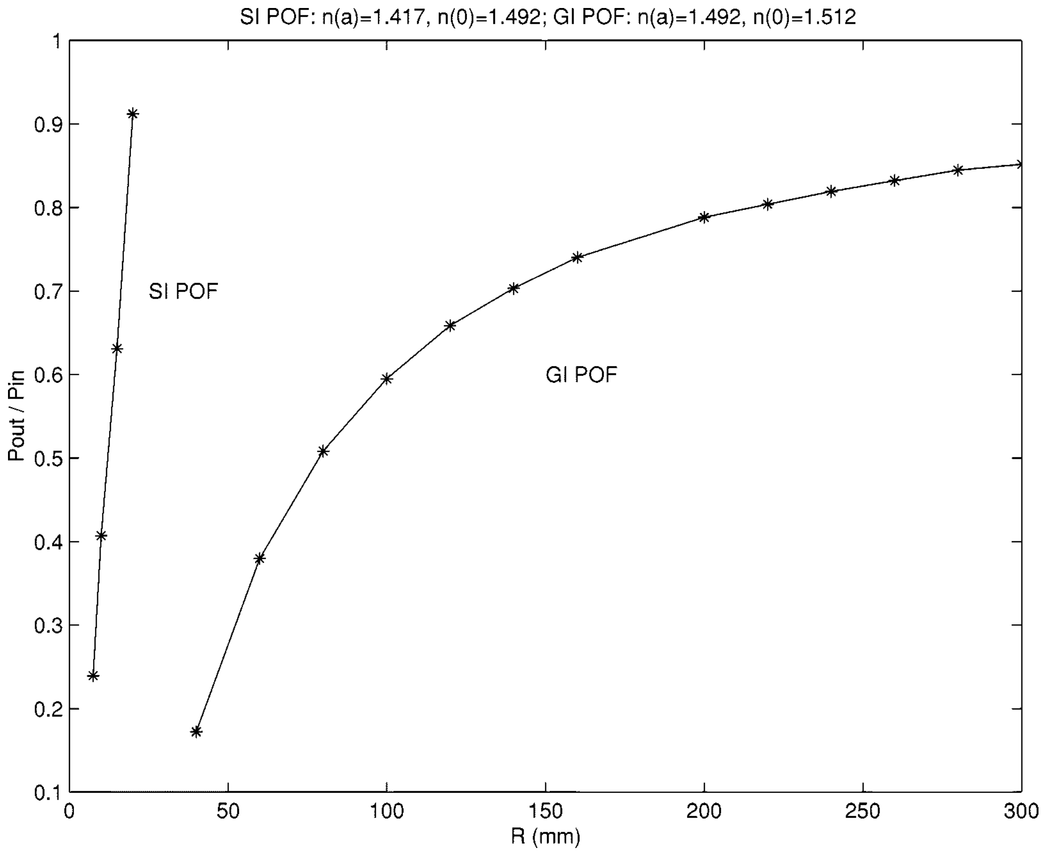

Fig. 6. SI POF: experimental results obtained for a typical step-index PMMA POF for one turn, as a function of the bend radius, shown for the sake of comparison with graded-index POF. GI POF: output power relative to the input power obtained for a 1-mm-diameter GI PMMA POF as a function of the bend radius for 1-1/4 turns.

a cylinder of fixed bend radius (10 mm). The slope of the curve tends to decrease as the length of the bent section increases, due to the gradual disappearance of tunneling rays.

B. Influence of Bend Radius for a Fixed Core Radius

The slope of the plot of the relative output power as a function of the bend radius decreases for larger bend radii. Therefore, for sufficiently large bend radii, we need not worry about small variations in the bend radius, since the corresponding change in the radiation losses would be insignificant. The critical radius of curvature is usually defined as the radius for which the output power relative to the input power is 0.5 (3 dB loss). This can be estimated for step-index fibers as the quotient between the core diameter and the index difference [3]. For graded-index fibers, the critical radius is approximately twice as large as that for step-index ones. These estimations yield an idea of the great influence of bending losses on graded-index fibers, although they only serve to estimate a single point of the curve of output powers as a function of the bend radius.

In Fig. 6, we show the output power relative to the input power obtained for a 1-mm-diameter GI PMMA POF as a function of the bend radius for 1-1/4 turns. We can note the tendency explained in the above paragraph. In this case, insignificant differences would be obtained between the curves with and without tunneling rays, due to the large core radius. We have only plotted one of the curves because the differences would be difficult to observe in a small figure. Regarding the estimation of the critical core radius commented on above, the result obtained with the formula is 100 mm, which corresponds to a relative power of 0.59 in our plot. The result would be more similar to 0.5 if we increased the number of turns, as explained before.

For the sake of comparison, in Fig. 6 we have plotted the experimental results that we have obtained for a typical step-index PMMA POF for one turn, as a function of the bend radius. In this case, much tighter bends still yield relatively low losses, due to the fact that there is a reflection at the core-cladding interface when the ray reaches it, which arises from the discontinuity in the refractive index when passing from the core to the cladding [2]. The formula for the critical radius estimates that this is of 13.3 mm, which is in good agreement with the experimental plot.

C. Combined Effect of Bend Radius and Profile Exponent

As we have already seen, the ratio of the output power relative to the input power ($Pout/Pin$) depends strongly on the bend radius. The decrease of power is faster as the bend radius decreases, which implies that special care must be taken with sharp bends. This quotient is also a function of the profile exponent q, although variations are not so great (Fig. 7). However, as q increases, the total radiation loss caused by large-bend radii increases faster than that caused by small-bend radii, provided that the number of turns is kept unchanged (see curves 2 and 3 of Fig. 8, which correspond to the results obtained for $q = 2.$ and $q = 2.17$, respectively, in the case of the “Lucina” fiber and

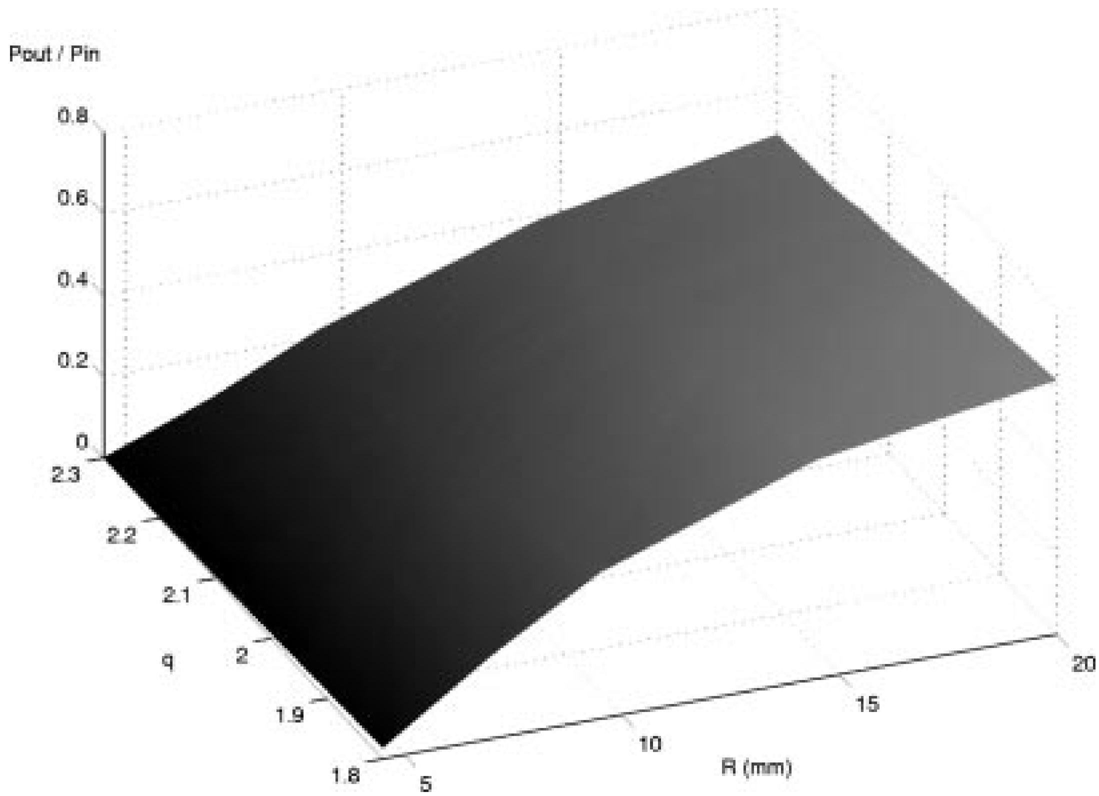

Fig. 7. Ratio of the output power relative to the input power as a function of the bend radius and the profile exponent for a core radius of 65 μm and core and cladding refractive indexes equal to 1.353 and 1.340, respectively.

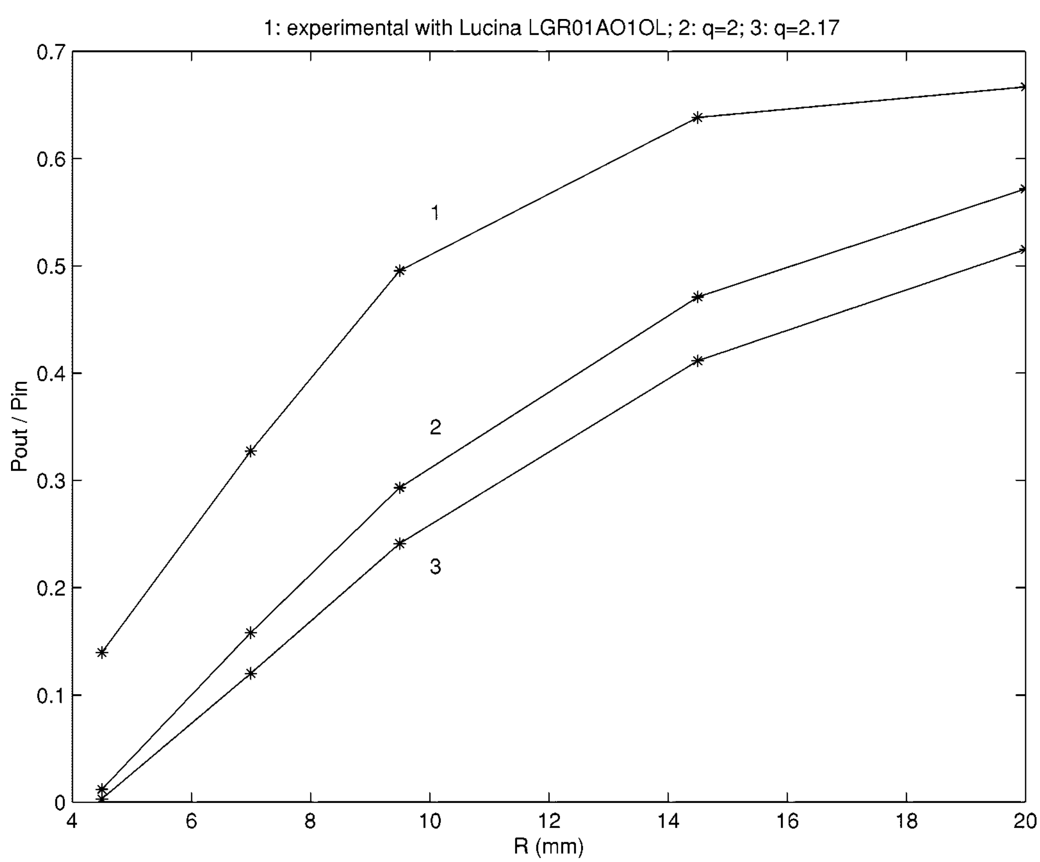

Fig. 8. Comparison between the experimental and the computational results obtained for the "Lucina" fiber as a function of the bend radius for 1-1/4 turns. 1: experimental; 2: theoretical for $q = 2$; 3: theoretical for $q = 2.17$.

1-1/4 turns). Since very sharp bends are usually avoided, this means that the choice of q will have a significant influence on bending losses, the lower values of q being preferable from this point of view.

In Fig. 8, we compare the experimental and the computational results obtained with the "Lucina" fiber as a function of the bend radius for 1–1/4 turns (Lucina LGR01AO1OL). The theoretical results do not take into account the interface between cladding and air, where reflections occur. In addition, the distribution of rays at the entrance of the bent section may differ from that considered in the computation, due to the fact that a very long straight fiber, without any bend, would be necessary for the real input distribution to coincide with the theoretical one. However, our computations serve to obtain an idea of the shape of the experimental curve.

VII. Conclusion

We have studied the influence of wavelength, core radius, refractive index difference, index profile, and bend radius on bending losses in GI POF. The method involves tracing of rays and use of Fresnel transmission coefficients to obtain the fraction of power that reaches the end of the bent section. The results show that the choice of the profile exponent has a significant influence on radiation losses, while the wavelength is much less influential. Its effect can be neglected for large core diameters (e.g., 1 mm). Most critical is the choice of the core radius, since bending losses approximately depend on the quotient between the bend radius and core radius. Therefore, the results obtained in this paper are scalable, especially when tunneling losses can be neglected. These results can help to decide about the convenient physical parameters of the new commercial GI POF. The influence of profile exponents different from two is included in the computational analysis for the first time.

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