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Experimental and theoretical study of optical losses in straight and bent Bragg fibres

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Abstract. **The leakage loss in straight and bent Bragg fibres has been studied experimentally and theoretically using five fibres differing in the core diameter, the number of layers in the Bragg mirror and their refractive indices. Simple analytical formulas have been derived within ray-optics theory which describe leakage and bending losses. The optical loss calculated using these formulas agrees well with our experimental data. Analysis of the theoretical and experimental results enables us to assess the effect of parameters of the waveguiding system on the optical loss in straight and bent fibres.**

Keywords: *fibre optics, Bragg fibre, optical losses, bending loss.*

1. Introduction

Bragg fibres (BFs) are among fibres having a photonic band gap. Even though BFs were proposed more than three decades ago [1, 2], they have attracted practical interest comparatively recently, after the optical loss in them had been brought to a sufficiently low level [3, 4]. This type of optical fibre is receiving much attention owing to its unique properties, noteworthy among which are the shift of the zero-dispersion point to wavelengths near 1 μm [5, 6] and the possibility of producing large mode area fibres with a low bend sensitivity [4, 7].

A typical BF comprises a core with a refractive index equal to or smaller than that of fused silica and a multilayer cylindrical cladding which acts as a Bragg mirror (Fig. 1). Light reflection from the boundaries of the layers, which can be adequately described by the Fresnel formulas, ensures confinement of the light in the fibre core. In contrast to fibres based on the principle of total internal reflection, BFs always have nonzero leakage losses, which should be taken into account in designing the fibre structure. A number of numerical and analytical approaches have been proposed to date for evaluating the optical loss in straight fibres (see e.g. Refs [8–11]), but they require sufficiently high professional skills. Moreover, the complexity of mathematical calculations makes it difficult – and, most frequently, impossible – to analyse the relationship between the parameters of BFs and the leakage loss. One exception is recent work by Feshchenko [12], who treated high-index layers as infinitely thin (delta-layers) and derived simple analytical formulas for evaluating the leakage loss in planar waveguides and straight BFs.

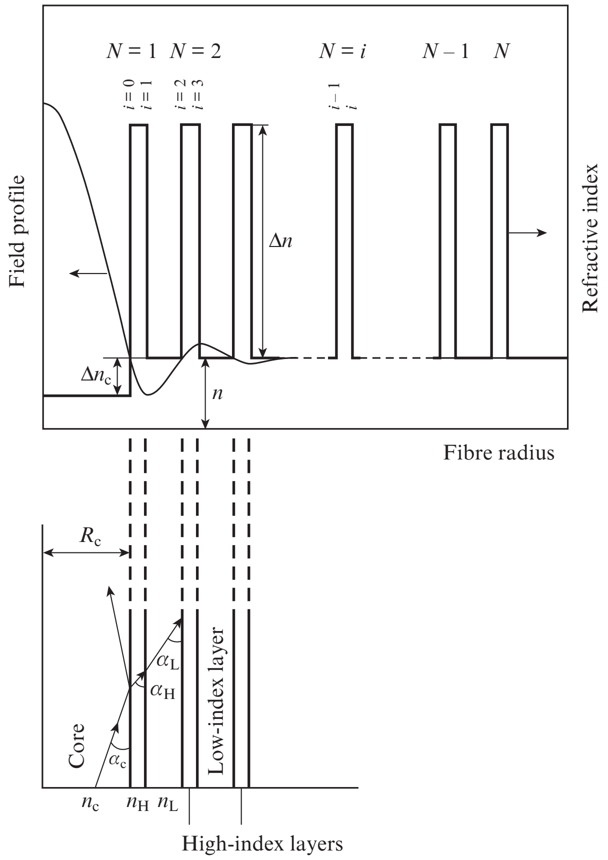

Figure 1. Bragg fibre structure.

Note that, in many cases, fibre has bends or is spooled for compactness, which may markedly increase optical losses. Mathematically, instead of calculating losses in a bent fibre, one can calculate those in a straight fibre with a distorted refractive index profile. The equivalent-index method takes advantage of this approach and is often used in numerical calculations of bent BFs [13, 14], but no detailed theoretical analysis of the bending loss in BFs has been presented to date.

In this paper, we report an experimental and theoretical study of loss mechanisms in BFs. We describe optical loss measurements on five BFs differing in parameters. Using ray-optics theory, we derive simple formulas for evaluating losses in straight and bent fibres. The calculation results agree well with our experimental data. The formulas can be used to

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analyse optical losses in relation to fibre parameters and identify those parameters having the strongest effect on the losses.

2. Theory

To derive formulas and analyse optical losses, we consider an idealised model system: a Bragg fibre with a silica core of radius R_c and refractive index n_c. The reflective cladding is taken to have a periodic structure: all the optically denser layers are identical in thickness, d_H, and refractive index, n_H. All the optically less dense layers of the cladding have a thickness d_L and refractive index n_L, differing from those of the denser layers. Therefore, the model fibre under consideration can be characterised by six parameters: core radius, R_c; index depression in the core relative to the optically less dense layers, n_c; number of high-index cladding layers, N; layer thicknesses d_H and d_L; and the index depression in the core relative to the optically less dense cladding layers, $\Delta n_c = n_L - n_c$. For simplicity, we take the refractive index of the environment to equal n_L, as is typically the case, and ignore effects related to the polymer coating of the fibre, as distinct from Uspenskii et al. [15].

As a rule, BFs are designed so that the cladding layers are quarter-wave thick at the operating wavelength of the fibre, λ:

$$d_{H(L)} = \frac{\lambda}{4 n_{H(L)} \sin\alpha_{H(L)}}, \tag{1}$$

where $\alpha_{H(L)}$ is the angle between the beam and fibre axis in the high-index (low-index) layers. This choice of layer thicknesses ensures the highest reflectivity of the Bragg mirror [16], reducing the number of parameters of the model Bragg fibre to four.

Silica-core fibres typically have a low index contrast: the index difference between their layers is much less than the average refractive index ($\Delta n, \Delta n_c \ll n_H, n_L, n_c$). Therefore, the refractive index of the optically less dense layers can be taken as the average index, n. Because of the low index contrast, the fibre modes can be described using the scalar wave equation [17, p. 242].

Note that the description of the physical properties of a waveguiding system composed of alternating optically denser and less dense layers can be simplified using ray theory in the $\lambda/R_c \ll 1$ approximation [2]. The field in a waveguide can then be represented as a combination of plane waves (rays) propagating at a certain angle, α_c, to the fibre axis. The low-loss modes of interest for us have small propagation angles, with $\sin\alpha \approx \tan\alpha \approx \alpha$.

For the fundamental mode, the propagation angle of rays in the core can be found from the condition that the field, described by the Bessel function $J_0(rn_c \sin\alpha_c 2\pi/\lambda)$, be zero at $r = R_c$. The applicability of this condition to Bragg fibres was discussed elsewhere [2, 14, 18]. It follows from this condition that

$$\alpha_c \approx \sin\alpha_c = z_{0,1}\lambda/(2\pi n_c R_c), \tag{2}$$

where $z_{0,1} \approx 2.4048$ is the first zero of the Bessel function $J_0(x)$. The propagation angles of rays in the cladding layers can be found using the principle of locality, which states that the reflection of a wave at any point can be considered by replacing a curvilinear (cylindrical in our case) boundary with its tangent plane. At small α angles, we obtain from Snell's law

$$\alpha_H^2 \approx \alpha_c^2 + 2(\Delta n + \Delta n_c)/n,$$
$$\alpha_L^2 \approx \alpha_c^2 + 2\Delta n_c/n, \tag{3}$$

where α_H and α_L are expressed through α_c, given by (2).

Following Snyder and Love [17, pp. 117, 573], we assume that local plane waves lose power only at reflection and turning points. Therefore, the optical loss in BFs can be expressed through the power transmission coefficient of the Bragg mirror, $T(\alpha_c)$. Because a fraction T of the ray power is lost at each reflection point and the separation between two successive reflection points is $4R_c/\tan\alpha_c$, the optical loss in a straight fibre is

$$A_{str} = \frac{20\tan\alpha_c}{R_c \ln 10} T(\alpha_c) \approx \frac{20\alpha_c}{R_c \ln 10} T(\alpha_c). \tag{4}$$

To find $T(\alpha_c)$, we again employ the principle of locality, reducing the problem to determining the transmission coefficient of a planar multilayer mirror. Using a well-known procedure for treating planar periodic structures composed of N quarter-wave layers [16] and taking into account that the angles under consideration are small, we obtain

$$T_N(\alpha_c) \approx \frac{4\alpha_c \alpha_L^{2N-1}}{\alpha_H^{2N}}. \tag{5}$$

Formulas (2)–(5) can be used to calculate the optical loss in a straight Bragg fibre with quarter-wave layers in a range around the operating wavelength.

A similar approach can be used to evaluate losses in bent BFs. It is then necessary to take into account that bends influence the α_c, α_H and α_L angles, which become dependent on the

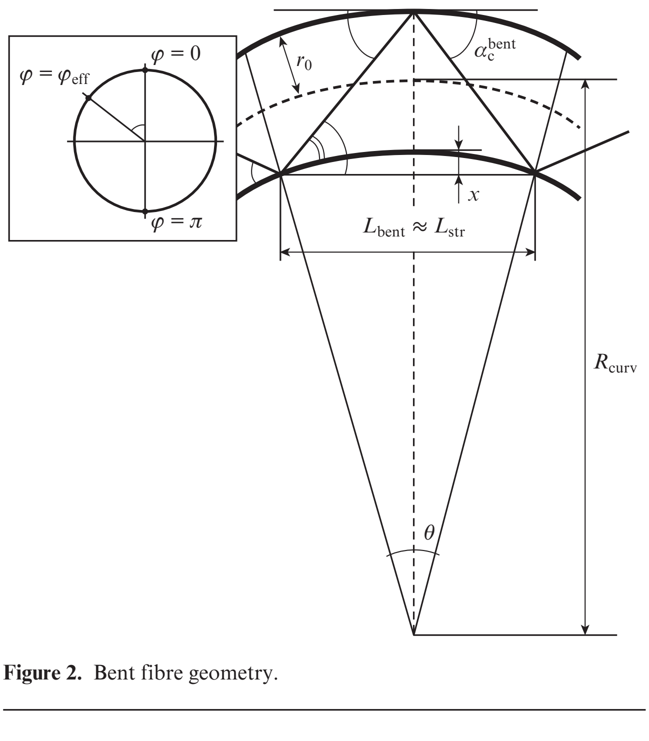


Figure 2. Bent fibre geometry.

azimuth angle, φ, between the bending plane and ray propagation plane. As seen in Fig. 2, a bend increases the propagation angle on the outer boundary (farther from the bend centre, at $\varphi = 0$) and reduces that on the inner ($\varphi = \pi$) boundary. The change in propagation angle has a maximum when light is incident on the outer surface in a direction lying in the bending plane, and decreases with increasing φ. With these changes, relation (4) takes the form

$$A_{\rm bent} \approx \frac{20}{R_{\rm c}\ln 10}\frac{1}{2\pi}\int_0^{2\pi}{\rm d}\varphi\,\alpha_{\rm c}^{\rm bent}(\varphi)\,T_{\rm bent}(\alpha_{\rm c}^{\rm bent}(\varphi))$$

$$= \frac{20}{R_{\rm c}\ln 10}\alpha_{\rm c}^{\rm bent}(\varphi_{\rm eff})\,T_{\rm bent}(\alpha_{\rm c}^{\rm bent}(\varphi_{\rm eff})), \qquad (6)$$

where we use the mean value theorem and introduce an effective azimuth angle, $\varphi_{\rm eff}$, which in general depends on the wavelength λ and bend radius $R_{\rm curv}$. Our calculations demonstrate that the use of a fixed effective angle $\varphi_{\rm eff} \approx 60°$ introduces no significant error.

Let us calculate the propagation angles $\alpha_{\rm H}^{\rm bent}$, $\alpha_{\rm L}^{\rm bent}$ and $\alpha_{\rm c}^{\rm bent}$ in a bent BF. A simple geometric analysis (Fig. 2) indicates that, in the bending plane ($\varphi = 0$), the angle of incidence on the outer surface is $\alpha_{\rm c}^{\rm bent} \approx \tan\alpha_{\rm c}^{\rm bent} = 2(2r_0 + x)/L_{\rm bent} = \alpha_{\rm c} + \theta/4$, where θ is the beam rotation angle relative to the bend centre, which determines the beam path in the bent fibre after two successive reflections. It can be shown that for any φ we have

$$\alpha_{\rm c}^{\rm bent}(\varphi) = \alpha_{\rm c} + \frac{\theta}{4}\cos\varphi = \alpha_{\rm c} + \frac{r_0}{R_{\rm curv}\alpha_{\rm c}}\cos\varphi. \qquad (7)$$

The Fresnel mechanism of light confinement in the BF core leads to partial localisation of mode rays in the fibre layers. Given this, the effective radius of the guiding part, r_0, is set to equal $R_0 + r/2$, where $r = Nd_{\rm H} + (N-1)d_{\rm L}$.

As above, the $\alpha_{\rm L}^{\rm bent}$ and $\alpha_{\rm H}^{\rm bent}$ angles can be found using Snell's law (3). As a result, the transmission of the Bragg mirror in a bent fibre, $T_N^{\rm bent}$, is given by

$$T_N^{\rm bent}(\varphi_{\rm eff}) = \frac{4\alpha_{\rm c}^{\rm bent}(\varphi_{\rm eff})[\alpha_{\rm L}^{\rm bent}(\varphi_{\rm eff})]^{2N-1}}{[\alpha_{\rm H}^{\rm bent}(\varphi_{\rm eff})]^{2N}}\left(\frac{1}{\sin^2\Phi_{\rm L}}\right)^{N-1}. \qquad (8)$$

The last factor in (8) is due to the fact that, because of the changes in propagation angles, the layers in a bent fibre are no longer quarter-wave thick, which gives rise to a phase difference between the propagating and reflected rays (which is only significant for the low-index layers):

$$\Phi_{\rm L} = \frac{\pi}{2}\frac{\alpha_{\rm L}^{\rm bent}(\varphi_{\rm eff})}{\alpha_{\rm L}}. \qquad (9)$$

Note that the above formulas for optical losses were derived for fibres with quarter-wave layers, which were assumed to have low leakage losses. However, strong bending may increase the propagation angles so that the condition $\alpha_{\rm L}^{\rm bent}/\alpha_{\rm L} = 2$ will be met and the phase difference $\Phi_{\rm L}$ will reach π. Reflections from different boundaries are then in antiphase, and further addition of layers does not reduce the transmission of the Bragg mirror. Reducing the bend radius down to the critical one, sharply increases the optical loss in the BF. Relation (6) then gives only a qualitative description of the bending effect on optical losses. From the condition $\alpha_{\rm L}^{\rm bent}/\alpha_{\rm L} \approx 2$, the critical bend radius can be estimated as

$$R_{\rm cr} \approx r_0\cos\varphi_{\rm eff}\left\{\alpha_{\rm c}^2\left[\left(4 + \frac{6\Delta n_{\rm c}}{\alpha_{\rm c}^2 n_{\rm L}}\right)^{1/2} - 1\right]\right\}^{-1}. \qquad (10)$$

3. Experimental procedure and results

To verify the above formulas, we explored five BFs differing in parameters of their core and Bragg mirror (Table 1). The fibres were drawn from MCVD preforms. To rule out the effect of the polymer coating on optical losses, the silica–polymer interface in the fibres was octagonal in shape [15] or they were coated with a polymer close in refractive index to undoped silica glass.

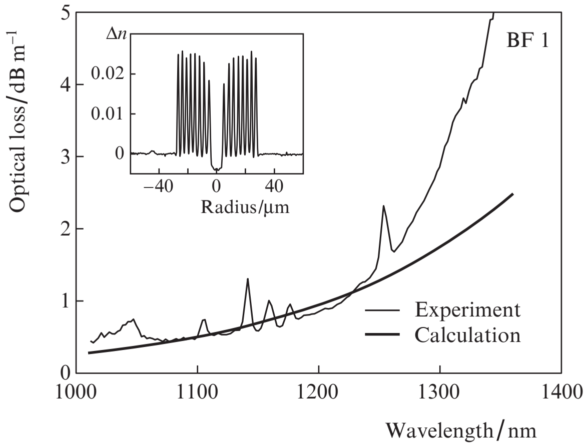
Optical losses were measured while consecutively reducing the fibre length (cut-back technique). To rule out the effect of modes excited in the high-index layers, radiation was coupled into and outcoupled from the fibre using a single-mode fibre with a cutoff wavelength near 0.8 μm. The single-mode and Bragg fibres were fusion-spliced, which ensured good data reproducibility. The sample length was varied from 2 to 6.5 m, depending on the output signal attenuation, and was adjusted so as to rule out the influence of higher order modes on the net optical loss in the fibre.

Figure 3 shows the loss spectra of three straight BFs with different parameters. The curves calculated from Eqn (4) are seen to agree well with the measured spectra in the range 1.1–1.2 μm, for which the fibres are intended. The reason for this is that, in this spectral range, rays reflected from different boundaries of the high-index layers in the Bragg structures interfere constructively, and the structure is near quarter-wave. Increasing or decreasing the wavelength of the propagating light changes the optical thickness of each layer and, as a consequence, increases the leakage loss. This is responsible for the discrepancy between the experimental and calculated curves.

Figure 4 plots the optical loss against inverse bend radius (zero abscissa corresponds to straight fibres). The curves, obtained using Eqn (6), are seen to adequately describe the bending effect on the optical loss in the fibre for both a slight increase in bending loss (20%–30%, fibre 1) and an increase by more than one order of magnitude (fibres 2, 3 and 5). The slight discrepancy between the calculated curve and data points for fibre 4 is most likely due to the few-mode operation of the fibre, which prevented us from accurately determining the loss in the fundamental mode LP_{01}.

Table 1. Parameters of the fibres.

Fibre no.	$D = 2R_{\rm c}$ /μm	$\Delta n = n_{\rm H} - n_{\rm L}$	$\Delta n_{\rm c} = n_{\rm L} - n_{\rm c}$	N	λ/μm	$R_{\rm cr}$/cm
1	9	0.025	0.0039	8	1.12	0.04
2	22	0.017	0.0000	3	1.06	1.30
3	38	0.012	0.0013	3	1.13	1.44
4	37	0.031	0.0010	3	1.26	1.41
5	39	0.012	0.0012	4	1.20	1.42



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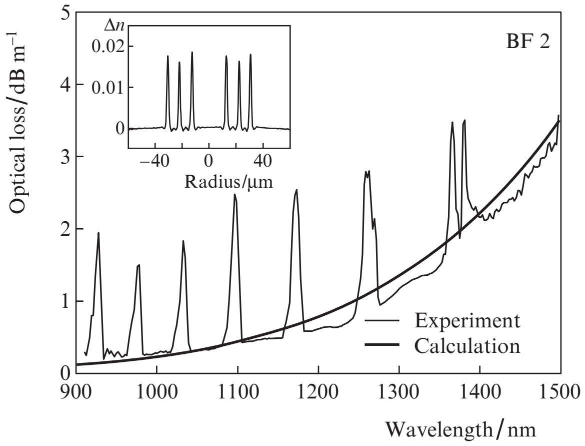

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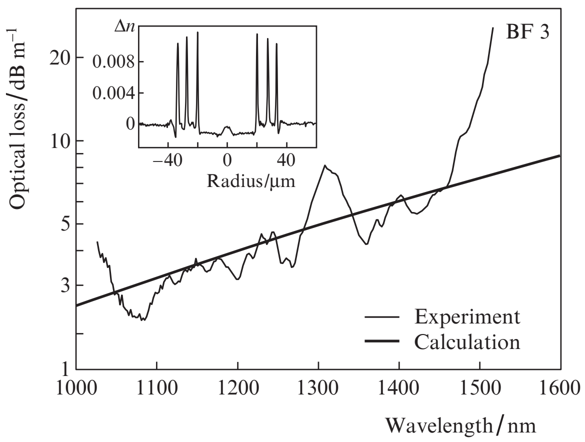

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Figure 3. Measured and calculated optical loss spectra of straight BFs. Insets: index profiles in the fibres.

The critical radii calculated by Eqn (10), which determine the applicability range of the above formulas, are listed in Table 1.

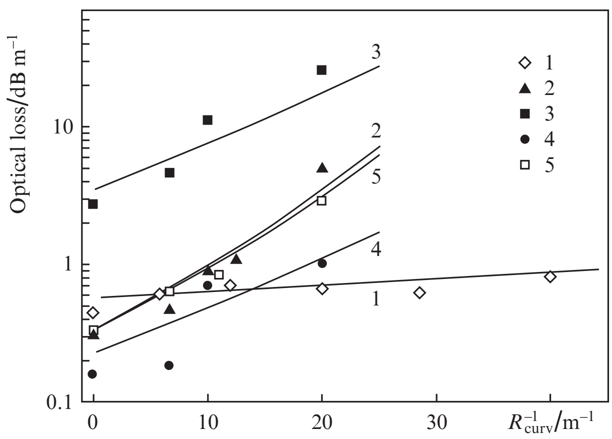

Figure 4. Optical loss against inverse bend radius for BFs 1–5.

4. Discussion

As seen in Figs 3 and 4, the optical loss calculated from Eqns (4) and (6) for the straight and bent BFs agrees well with the experimental data. An important point is that the simple relations obtained allow us to follow the key trends in the variation of the optical loss in the BFs with their parameters. In deriving formulas (5) and (8), we considered BFs with a low index contrast, a small number of layers and high reflectivity of the interfaces between the denser and less dense layers of the mirror. Therefore, the conditions $\Delta n_{\rm c} \ll \Delta n$ and $\alpha_{\rm c}^2 n/2 \ll \Delta n$ were met. It can be shown that in the case of straight fibres we have

$$T_N \sim \frac{1}{n^{1/2}}\frac{\lambda}{R_{\rm c}}\frac{(\Delta n_{\rm c} + n\alpha_{\rm c}^2/2)^{N-1/2}}{\Delta n^N}. \qquad (11)$$

It follows from (11) that the optical loss in straight fibres can be reduced by increasing the number of layers in the Bragg mirror, N, and the index contrast between the denser and less dense cladding layers, Δn, as supported by comparison of the optical loss in straight fibres 3–5 (the data points at $1/R = 0$ in Fig. 4). By contrast, increasing the index depression in the core increases the optical loss. It is worth pointing out that the optical loss depends in addition on the $\lambda/R_{\rm curv}$ ratio: the relation is linear for $\Delta n_{\rm c} \gg 0.5n\alpha_{\rm c}^2$ and a power law with an exponent $2N$ for $\Delta n_{\rm c} \ll 0.5n\alpha_{\rm c}^2$. The rise in leakage loss with increasing wavelength is well seen in Fig. 3. The data can also be illustrated by comparing fibre 1 to the other fibres. Because of the large index depression in the core and the relatively small core radius, the optical loss in a straight portion of fibre 1 is rather high, despite the large number of layers ($N = 8$) and the high index contrast in the Bragg mirror ($\Delta n = 0.025$) (Fig. 3a).

Consider now how the bend sensitivity of the fibres depends on their parameters. The bend sensitivity here means the ratio of the optical loss in a bent fibre to the leakage loss in a straight fibre. When the bend radius is varied, the bend sensitivity is determined by the variation in the slope of the optical loss curve at the operating wavelength (Fig. 4).

Using relation (6) for the loss in a bent fibre, we can show that the last factor in (8), responsible for the variation in the phase difference between rays reflected from different layers, is close to unity at relatively weak bends and its contribution

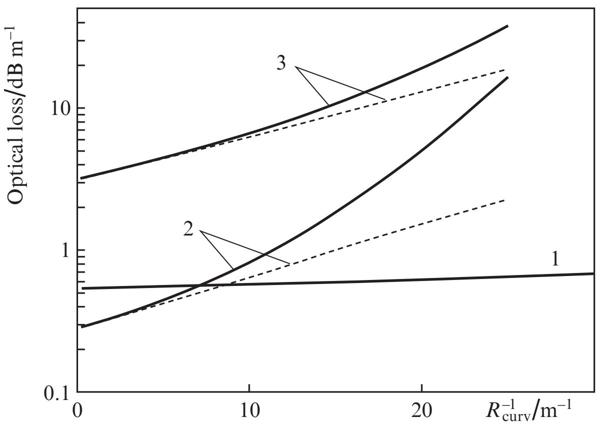

Figure 5. Optical loss calculated from (6) with (solid lines) and without (dashed lines) allowance for the phase factor against inverse bend radius for BFs 1–3.

to the net transmission coefficient is substantially smaller than that of the term due to the reflectivity of the layers in the Bragg mirror. Figure 5 shows the calculated optical loss as a function of inverse bend radius with and without allowance for the phase factor.

The observed behaviour of the loss allows us to neglect the phase-related factor in (8) in qualitative analysis of the bending loss. The sensitivity of a fibre is then given by

$$\frac{T_N^{\mathrm{bent}}}{T_N} \cong \frac{\alpha_{\mathrm{c}}^{\mathrm{bent}}}{\alpha_{\mathrm{c}}}\left(\frac{\alpha_{\mathrm{L}}^{\mathrm{bent}}}{\alpha_{\mathrm{L}}}\right)^{2N-1}\left(\frac{\alpha_{\mathrm{H}}}{\alpha_{\mathrm{H}}^{\mathrm{bent}}}\right)^{2N}. \tag{12}$$

Because the light propagation angles in the denser optical layers vary considerably more slowly, relation (12) reduces to the form

$$\frac{T_N^{\mathrm{bent}}}{T_N} \cong \frac{\alpha_{\mathrm{c}}^{\mathrm{bent}}}{\alpha_{\mathrm{c}}}\left(\frac{\alpha_{\mathrm{L}}^{\mathrm{bent}}}{\alpha_{\mathrm{L}}}\right)^{2N-1}$$

$$= \frac{\alpha_{\mathrm{c}}^{\mathrm{bent}}}{\alpha_{\mathrm{c}}}\left[\frac{(\alpha_{\mathrm{c}}^{\mathrm{bent}})^2 + 2\Delta n_{\mathrm{c}}/n}{\alpha_{\mathrm{c}}^2 + 2\Delta n_{\mathrm{c}}/n}\right]^{N-1/2}. \tag{13}$$

Therefore, the bend sensitivity of the fibres is determined by the light propagation angle and index depression in the core and the number of layers, N. Since we consider bend radii well below the critical radius (10), the variation in α_{L} is limited by the condition $\alpha_{\mathrm{L}}^{\mathrm{bent}} - \alpha_{\mathrm{L}} \ll \alpha_{\mathrm{L}}$ (in fact, the variation of the $\alpha_{\mathrm{L}}^{\mathrm{bent}}/\alpha_{\mathrm{L}}$ ratio from unity determines the variation in phase factor, which, as shown above, varies insignificantly at weak bends). For this reason, the addition of one high-index layer has a rather weak effect on the bend sensitivity.

The example of fibres 3–5, which have identical parameters of the core ($\Delta n_{\mathrm{c}} \sim 0.001$, $R_{\mathrm{c}} \sim 20$ μm), illustrates the effect of the parameters of the Bragg mirror on the optical loss. The fibres differ in that the Δn in fibre 4 exceeds that in fibre 3, and fibre 5 has an increased number of layers, N. It can be seen from Fig. 4 that these fibres are comparable in bend sensitivity (slope of the curves). Accordingly, a reduction in the optical loss in straight fibres (fibres 4 and 5 against fibre 3) leads to lower optical losses in bent fibres. The effect of the index contrast in the Bragg mirror on the optical loss in bent fibres was observed earlier [19], whereas a reduction in the optical loss in bent BFs upon an increase in the number of layers has been predicted and demonstrated for the first time.

Returning to Eqn (13), consider two limiting cases: $\Delta n_{\mathrm{c}} \gg 0.5n\alpha_{\mathrm{c}}$ and $\Delta n_{\mathrm{c}} \ll 0.5n\alpha_{\mathrm{c}}^2$. According to (13), the bend sensitivity for $\Delta n_{\mathrm{c}} \gg 0.5n\alpha_{\mathrm{c}}$ is given by

$$\frac{T_N^{\mathrm{bent}}}{T_N} \backsim 1 + \frac{f(R_{\mathrm{curv}})}{\alpha_{\mathrm{c}}^2}, \tag{14a}$$

and that for $\Delta n_{\mathrm{c}} \ll 0.5n\alpha_{\mathrm{c}}^2$ is

$$\frac{T_N^{\mathrm{bent}}}{T_N} \backsim \left(1 + \frac{f(R_{\mathrm{curv}})}{\alpha_{\mathrm{c}}^2}\right)^{2N}. \tag{14b}$$

where $f(R_{\mathrm{curv}}) = r_0/(R_{\mathrm{curv}}\sin\varphi)$.

Because α_{c} is a function of R_{c} [see (2)], a decrease in the core radius will lead to a reduction in the bend sensitivity of the fibre. As seen from (14a) and (14b), an increase in index depression in the core from zero to $\Delta n_{\mathrm{c}} \gg 0.5n\alpha_{\mathrm{c}}^2$ leads to a change in functional dependence (an exponent of unity instead of $2N$) and, as a consequence, to a reduction in bend sensitivity (by a factor of $2N$ for $f(R_{\mathrm{curv}}) \ll \alpha_{\mathrm{c}}^2$). It is also seen in Fig. 4 that the bend radius has an insignificant effect on the leakage loss in fibre 1, which has the smallest core radius and the largest index depression. In particular, a bend of 2.5 cm radius increases the optical loss in fibre 1 by only a factor of 1.6.

5. Conclusions

The present experimental and theoretical results indicate that a ray-optics model that takes into account only reflections from the interfaces in the Bragg structure and interference between neighbouring interfaces makes it possible to adequately evaluate the optical loss in both straight and bent Bragg fibres. The formulas obtained enabled us to establish the relationship between parameters of Bragg fibres and the optical loss in straight Bragg fibres and to assess the bending effect on optical losses.

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