Predicting macrobending loss for large-mode area photonic crystal fibers

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Abstract: We report on an easy-to-evaluate expression for the prediction of the bend-loss for a large mode area photonic crystal fiber (PCF) with a triangular air-hole lattice. The expression is based on a recently proposed formulation of the V-parameter for a PCF and contains no free parameters. The validity of the expression is verified experimentally for varying fiber parameters as well as bend radius. The typical deviation between the position of the measured and the predicted bend loss edge is within measurement uncertainty.

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1. Introduction

In solid-core photonic crystal fibers (PCF) the air-silica microstructured cladding (see Fig. 1) gives rise to a variety of novel phenomena [1] including large-mode area (LMA) endlessly-single mode operation [2]. Though PCFs typically have optical properties very different from that of standard fibers they of course share some of the overall properties such as the susceptibility of the attenuation to macro-bending.

Macrobending-induced attenuation in PCFs has been addressed both experimentally as well as theoretically/numerically in a number of papers [2, 3, 4, 5, 6]. However, predicting bending-loss is no simple task and typically involves a full numerical solution of Maxwell’s equations as well as use of a phenomenological free parameter, e.g. an effective core radius. In this paper we revisit the problem and show how macro-bending loss measurements on high-quality PCFs can be predicted with high accuracy using easy-to-evaluate empirical relations.

2. Predicting macro-bending loss

Predictions of macro-bending induced attenuation in photonic crystal fibers have been made using various approaches including antenna-theory for bent standard fibers [3, 4], coupling-length criteria [2, 5], and phenomenological models within the tilted-index representation [6]. Here, we also apply the antenna-theory of Sakai and Kimura [7, 8], but contrary to Refs. [3, 4] we make a full transformation of standard-fiber parameters such as $\Delta$, $W$, and $V$ [9] to fiber parameters appropriate to high-index contrast PCFs with a triangular arrangement of air holes. In the large-mode area limit we get (see Appendix)

$$\alpha \Lambda' \frac{1}{8} \frac{1}{6\pi} \frac{\Lambda^2}{n_S A_{\text{eff}}} \frac{\lambda}{\Lambda} \frac{1}{R} \frac{1}{6\pi^2} \frac{1}{n_S^2} \frac{\lambda}{\Lambda} \frac{2}{V_{\text{PCF}}} F^3(x) \exp(-2\alpha z) \quad (1)$$

for the power-decay, $P(z) = P(0) \exp(-2\alpha z)$, along the fiber. For a conversion to a dB-scale $\alpha$ should be multiplied by $20 \log_{10}(e) \approx 6.02$. In Eq. (1), $R$ is the bending radius, $A_{\text{eff}}$ is the effective area [10], $n_S$ is the index of silica, and

$$V_{\text{PCF}} = \Lambda \frac{q}{\beta^2} \frac{\beta^2}{\beta^2_{\text{cl}}}$$

is the recently introduced effective V-parameter of a PCF [11]. The strength of our formulation is that it contains no free parameters (such as an arbitrary core radius) and furthermore empirical expressions, depending only on $\lambda/\Lambda$ and $d/\Lambda$, have been given recently for both $A_{\text{eff}}$ and $V_{\text{PCF}}$ [12, 13].

From the function $F(x)$ we may derive the parametric dependence of the critical bending radius $R$. The function increases dramatically when the argument is less than unity and thus we may define a critical bending radius from $x = 1$ where $F(x) = 1$. Typically the PCF is operated close to cut-off where $V_{\text{PCF}} = \pi$ [11] so that the argument may be written as

| Core Diameter [\(\mu m\)] | LMA-20 | LMA-25 | LMA-35 |
|-----------------------------|--------|--------|--------|
| 20.0                        | 24.5   | 34.7   |
| 13.20                       | 16.35  | 23.15  |
| 0.485                       | 0.500  | 0.500  |

Fig. 1. Structural data for the LMA fibers which all have a cross-section with a triangular arrangement of air-holes running along the full length of the fiber.
Fig. 2. Macro-bending loss for the LMA-20 fiber for bending radii of $R=8$ cm (red, solid curve) and $R=16$ cm (black, solid curve). Predictions of Eq. (1) are also included (dashed curves).

$$\frac{1}{\pi} \frac{1}{6\pi^2 \frac{n_2^2}{n_1^2}} \frac{R}{\Lambda} \left( \frac{\lambda}{\Lambda} \right)^2 \propto \frac{\Lambda^3}{\lambda^2}$$  \hspace{1cm} (3)

This dependence was first reported and experimentally confirmed by Birks et al. [2] and recently a pre-factor of order unity was also found experimentally in Ref. [5].

Fig. 3. Macro-bending loss for the LMA-25 fiber for bending radius of $R=16$ cm (solid curve). Predictions of Eq. (1) are also included (dashed curve).
3. Experimental results

We have fabricated three LMA fibers by the stack-and-pull method and characterized them using the conventional cut-back technique. All three fibers have a triangular air-hole array and a solid core formed by a single missing air-hole in the center of the structure, see Fig. 1. For the LMA-20 macro-bending loss has been measured for bending radii of $R=8$ cm and $R=16$ cm and the results are shown in Fig. 2. The predictions of Eq. (1) are also included. It is emphasized that the predictions are based on the empirical relations for $A_{\text{eff}}$ and $V_{\text{PCF}}$ provided in Refs. [12] and [13] respectively and therefore do not require any numerical calculations. Similar results are shown in Figs. 3 and 4 for the LMA-25 and LMA-35 fibers, respectively.

4. Discussion and conclusion

The PCF, in theory, exhibits both a short and long-wavelength bend-edge. However, the results presented here only indicate a short-wavelength bend-edge. The reason for this is that the long-wavelength bend-edge occurs for $\lambda \Lambda = 2$ [3]. For typical LMA-PCFs it is therefore located in the non-transparent wavelength regime of silica.

In conclusion we have demonstrated that macro-bending loss measurements on high-quality PCFs can be predicted with good accuracy using easy-to-evaluate empirical relations with only $d$ and $\Lambda$ as input parameters. Since macro-bending attenuation for many purposes and applications is the limiting factor we believe that the present results will be useful in practical designs of optical systems employing photonic crystal fibers.

Appendix

The starting point is the bending-loss formula for a Gaussian mode in a standard-fiber [7, 8]

$$\alpha = \frac{p}{8} \frac{1}{A_{\text{eff}}} \frac{\rho}{W} \exp \left( \frac{4 \frac{R}{\rho} \frac{\Lambda}{\rho^2} W^3}{W^2 \frac{R}{\rho} + \frac{\nu^2}{2 \lambda W}} \right)$$  (4)
where $A_{\text{eff}}$ is the effective area, $\rho$ is the core radius, $R$ is the bending radius, and the standard-fiber parameters are given by [7, 9]

$$\Delta = \frac{\sin^2 \theta_c}{2}; \quad V = \beta \rho \sin \theta_c; \quad W = \rho \beta^2 \frac{q}{F};$$

(5)

Substituting these parameters into Eq. (4) we get

$$\alpha \Lambda' = \frac{1}{8} \frac{2 \pi A_{\text{eff}}^2}{3} \frac{1}{\Lambda' \beta} \frac{2 R V_{\text{PCF}}^3}{3 \Lambda (\beta \Lambda)^2}$$

(6)

in the relevant limit where $R \gg \rho$. Here, $F$ and $V_{\text{PCF}}$ in Eqs. (1) and (2) have been introduced. For large-mode area fibers we make a further simplification for the isolated propagation constant; using that $\beta = 2 \pi n_{\text{eff}} = \lambda' 2 \pi n_S = \lambda$ we arrive at Eq. (1).

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