Microbending effects in hollow-core photonic bandgap fibers

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Abstract *We developed a model for the study of how microbends affect the operation of hollow-core photonic bandgap fibers. Increased loss due to intermodal coupling is predicted. Preliminary experimental observations are in good agreement with the model's predictions.*

Introduction

Over the past few years, several ground-breaking experiments have demonstrated the potential of hollow-core photonic bandgap fibers (HCPBGFs) for low-latency data transmission over a few or few tens of kilometres[1,2]. Currently, efforts are being made to reduce the loss in these fibers to levels comparable to that of conventional single mode fibers. If achieved, the combination of low loss, low nonlinearity and low latency will establish HCPBGFs as strong contenders for data transmission applications.

While it is by now established that HCPBGFs are robust to macrobending[3], and that their loss is fundamentally limited by scattering from surface roughness[4], other potential extrinsic sources of attenuation are less well understood or studied. One such example potentially leading to loss and/or intermodal coupling is microbending to which the fiber is subject as it is rewound onto a drum or cabled. In single mode fibers, the effect of such microbends along the fiber axis is to couple some of the guided power to radiation modes, resulting in excess loss for the fiber. Here for the first time, we study the physical effects caused by the presence of microbends in HCPBGFs. Unlike in single mode fibers, we find that random microbends predominantly cause power coupling between modes of adjacent azimuthal mode number. When significant differential modal loss is present, the added mode coupling not only results in intermodal cross-talk, but also provides an avenue for additional fiber loss.

Theory of microbending

In conventional fiber types, the treatment of microbends or other micro-deformations is usually performed via a coupled mode formalism[5]. Here we adopt the approach pioneered by Taylor[6] and Petermann[7] and start with the study of a single corner bend of angle 2ϕ in the x direction as shown in Fig.1.

In the straight sections, the solutions to the wave equation $\widehat{\Theta}u = \Lambda_u u$ ($\widehat{\Theta} = \nabla^2 - \varepsilon k_0^2$ and $\Lambda_u = \beta_u^2$) can be classified as guided modes $|m\rangle$ and radiation modes $|\rho\rangle$ which form a complete and orthogonal set. These can be further normalized so that

$$\langle u|u'\rangle = \iint u^* u' dA = \delta_{uu'} \qquad (1)$$

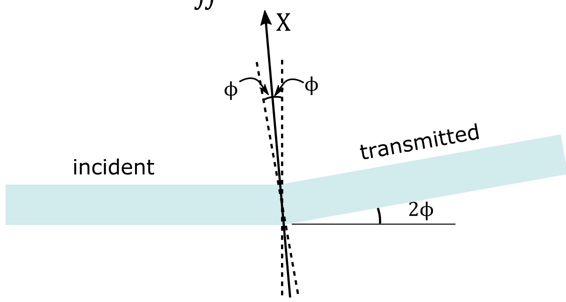

Fig.1: Direction change of angle 2ϕ at a corner bend in a waveguide.

where δ is a Kronecker delta and the spatial integration is over the entire fiber cross-section. An arbitrary field can therefore be expanded as:

$$f(x,y) = \sum_m a_m|m\rangle + \sum_\rho a_\rho|\rho\rangle \qquad (2)$$

where the sum over the radiation modes is to be interpreted as an integral. Let us now suppose that the pure guided mode $|i\rangle$ carrying unit power is incident at the bend. If we assume that (i) the angle 2ϕ of the bend is very small and that therefore (ii) the reflected power is negligible, the incident and transmitted fields can be matched along the X plane. Doing so by expanding the transmitted field as in Eq. (1) results in the coefficients given by[6]:

$$a_m = \langle m|\widehat{H}|i\rangle = \iint u_m^*(\widehat{H}u_i)dA \qquad (3)$$

with $\widehat{H} = j\beta_0\phi x$. This indicates that when the fiber has cylindrical symmetry ($x = r\cos\theta$), only modes with azimuthal mode number difference of ± 1 will exchange power. The total power coupled out of the incident mode is obtained as:

$$\Delta P_i = \sum_{m,\rho\neq i} a_m^* a_m = \sum_{m,\rho\neq i} \langle i|\widehat{H}^*|m\rangle\langle m|\widehat{H}|i\rangle \qquad (4)$$

Exploiting the properties of complete function sets[6], this equation becomes simply:

$$\Delta P_i = \langle i|\widehat{H}^*\widehat{H}|i\rangle = \beta_0^2\phi^2\langle i|x^2|i\rangle \qquad (5)$$

It emerges therefore that knowledge of the mode $|i\rangle$ alone suffices to characterise how it is effected by the bend. The total power coupled out of the mode is proportional to the square of the spot radius which may be defined as $\langle i|x^2|i\rangle$. As a result, fibers with smaller core radii are less vulnerable to microbending induced power loss, the magnitude of which grows approximately as R_c^2, with R_c the core radius. In single-mode fibers or in cases where differential modal losses are very large, Eq.(5) would represent the total power lost at the bend. When multiple guided modes are supported in the fiber, the power lost to guided modes is calculated as the sum:

$$\Delta P_g = \sum\nolimits_{m\neq i} a_m^* a_m \qquad (6)$$

The power directly lost to radiation modes is therefore $\Delta P_r = \Delta P_i - \Delta P_g$.

In Fig. 2 we apply these formulae numerically to the 19c HCPBGF reported in [1]. Fig. 2(b) shows that the dominant effect of the bend is to transfer power between the fundamental and other air guided modes, with negligible additional power transfer to radiation modes. Specifically the LP_{11} mode group receives in excess of 97% of the overall power transferred out of the fundamental mode.

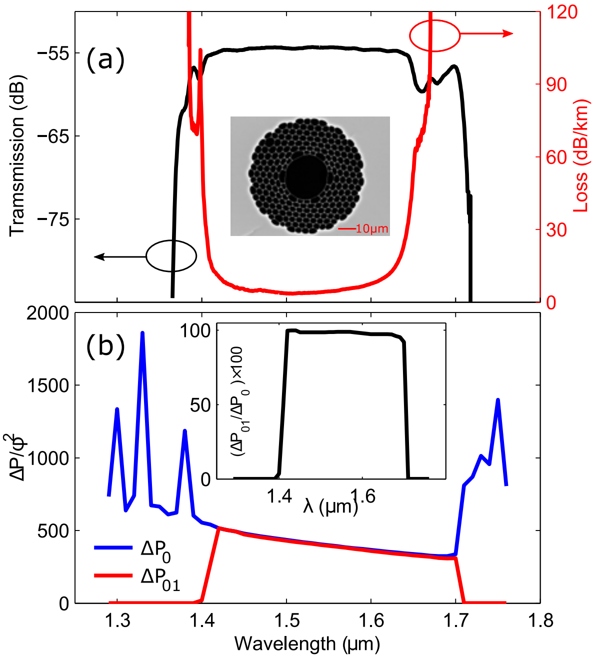

Fig.2: (a) Measured transmission, cutback loss and cross-section of a fabricated 19c fiber. (b) Normalized power coupled out of the fundamental mode at a corner bend. The inset shows the ratio of this power coupled to LP_{11}. The total power coupled out is labelled ΔP_0 and the fraction coupled to LP_{11} is ΔP_{01}

In the study of microbends, we are often interested in the effect of random and continuously distributed bends along the length of the fiber. In such cases, the power couples out of the mode $|i\rangle$ at a rate per unit distance of[7,8]:

$$\gamma_i = \sum_{m,\,\rho\neq i} C(\beta_i - \beta_m)\, \beta_0^2 \langle i|x|m\rangle\langle m|x|i\rangle \qquad (7)$$

where $C(\Delta\beta)$ is the power spectral density of the curvature function from the random microbends[9]. Approximating $\Delta\beta_{im} = \beta_i - \beta_m = (\Lambda_i - \Lambda_m)/2\beta_0$ ($\Lambda_i = \beta_i^2$), one rewrites this expression as

$$\gamma_i = \beta_0^2 \sum_{m,\,\rho\neq i} \Phi(\Lambda_m)\, \langle i|x|m\rangle\langle m|x|i\rangle \qquad (8)$$

with $\Phi(\Lambda_m) = C((\Lambda_i - \Lambda_m)/2\beta_0)$. This allows us to exploit again the properties of complete sets of eigenvectors to simplify this as[8]:

$$\gamma_i = \langle i|x\Phi(\widehat{\Theta})x|i\rangle \qquad (9)$$

As before, the power exchange rate per unit length between two guided modes is:

$$\gamma_{im} = C(\Delta\beta_{im})\beta_0^2 |\langle i|x|m\rangle|^2 \qquad (10)$$

and the direct loss coefficient to radiation is simply:

$$\alpha_i = \gamma_i - \sum \gamma_{im} \qquad (11)$$

Although eliminating the need to know all the radiation modes supported by the fiber, this expression can be computed only if the function Φ takes a simple polynomial form, which does not happen in most practical cases. However, Eq.(3) can allow us to put reasonably close bounds on the loss incurred as a result of microbends. The cases of interest to which we will limit ourselves in this paper are those in which the curvature PSD is a rapidly decaying function of the spatial frequency. When this assumption holds, if we study the loss of the fundamental mode (labelled 0), $\Delta\beta$ is smallest for the LP_{11} mode group (labelled 1) and an upper loss limit is simply:

$$\alpha_{max} = \beta_0^2 C(\Delta\beta_{01})\langle 0|x^2|0\rangle - \sum \gamma_{0m} \qquad (12)$$

Having observed previously that over 97% of the scattered power goes to the LP_{11} mode group, a more relaxed limit is, with good approximation:

$$\alpha_{max} = \beta_0^2 C(\Delta\beta_{01})(\langle 0|x^2|0\rangle - |\langle 0|x^2|1\rangle|^2) \qquad (13)$$

Figure 3 shows the calculated coupling efficiency between fundamental and LP_{11} mode of the fibre in Fig.2 (eq. 10), together with the upper radiation loss limit (eq. 13) in the cases where the PSD is an inverse power law $C(\Delta\beta) = 1/\Delta\beta^2$ and a Gaussian. For the Gaussian spectrum we have taken a correlation length of $L_c = 1mm$. In both cases, direct coupling to radiation is nearly negligible. The dominant effect of the random microbends is thus the power exchange between modes with adjacent azimuthal mode number. For the fundamental mode, this coupling occurs predominantly to the LP_{11} mode. Although direct coupling to radiation may be negligible, the power exchange among the modes can significantly impact the operation of the fiber. It induces intermodal cross talk in multimode operation and provides an additional route for loss when large differential modal losses are present.

From Fig.3, one also visually observes the effect of the curvature PSD on the wavelength dependence of the microbending effects. As the Gaussian PSD decreases more rapidly with spatial frequency, the slope of the loss curve on

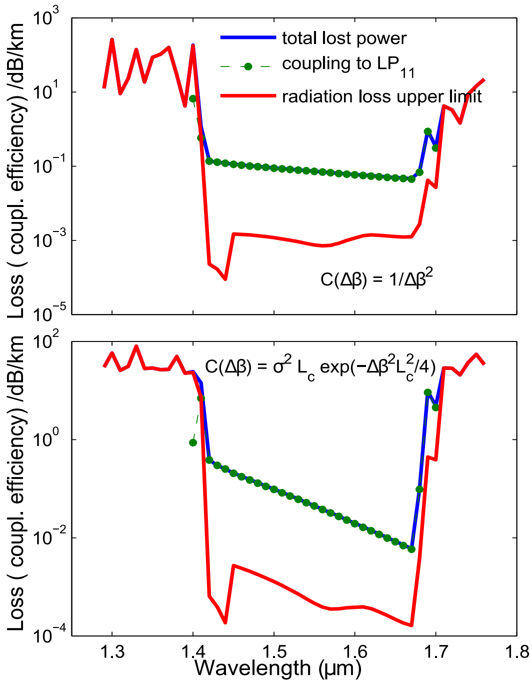

Fig. 3 Random microbend induced mode coupling and upper loss limit for the fundamental mode in a 19c HC-PBGF. (a) the curvature PSD follows an inverse power law and (b) a Gaussian with curvature $rms\ \sigma = 0.1$ and correlation length $L_c = \ 1mm$.

the semilog plot is much steeper.

Experimental verification

To test the theory described in the previous section, we performed a simple experiment whose setup is shown in Fig.4. Light from a white light source was launched into a 60m long HCPBGF sample taken from the 11km fiber reported in ref. [2]. The transmission was then recorded using the OSA when the fiber was loose. To simulate a single corner bend, the fiber was crossed with itself 5m away from the OSA and a 50g load added at the point of crossing. The transmission was again recorded and subtracted from the transmission under loose conditions to obtain the loss. The recorded transmission spectra under loose and crossing conditions and the loss are the continuous black, purple and green lines in Fig.4.

Having extracted the fiber profile from a high resolution scanning electron microscope image, we used a finite element solver to find its modes and calculated the total power coupled out of the fundamental mode with Eq. (5). When we assume that the angle sustained at the corner bend is $\phi = 0.4°$, the calculated loss shown as the red dashed line in Fig.4 agrees remarkably well (note the slope, in particular) with the experiment.

While more careful experiments are needed to study the effect of *random* bends, this agreement confirms and validates the predicted effects for a

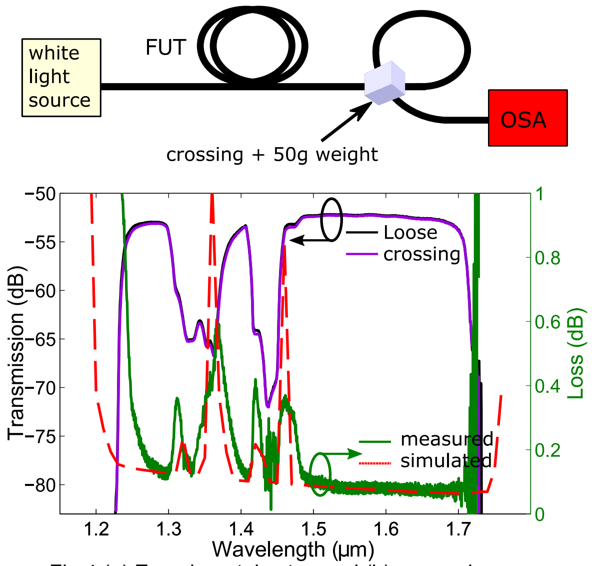

Fig.4 (a) Experimental setup and (b) comparison between measured loss at a single corner bend and corresponding simulation.

single corner bend: (i) loss at the bend is proportional to the square of the spot radius and (ii) inversely proportional to the square of the wavelength.

Conclusion

We have presented for the first time a theoretical treatment of microbending effects in HC-PBGFs. In most practical cases, the dominant impact of microbends is to cause power exchange between the guided modes of the fiber. The expressions derived show a very good agreement with our initial experiments. We believe that understanding the consequences of microbends will be key to develop practical steps to produce microbend robust fibres with lower overall loss.

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