

Models for guidance in kagome-structured hollow-core photonic crystal fibres

G. J. Pearce¹, G. S. Wiederhecker^{1,2}, C. G. Poulton¹, S. Burger³, and P. St. J. Russell^{1*}

¹Max Planck Research Group (IOIP), Günther-Scharowsky-Str. 1 / Bau 24, 91052 Erlangen, Germany

²CePOF, Instituto de Física, Universidade Estadual de Campinas, 13.083-970 Campinas SP, Brazil

³Zuse Institute Berlin (ZIB), Takustr. 7, 14195 Berlin, Germany

*Corresponding author: russell@optik.uni-erlangen.de

<http://www.pcfibre.com>

Abstract: We demonstrate by numerical simulation that the general features of the loss spectrum of photonic crystal fibres (PCF) with a kagome structure can be explained by simple models consisting of thin concentric hexagons or rings of glass in air. These easily analysed models provide increased understanding of the mechanism of guidance in kagome PCF, and suggest ways in which the high-loss resonances in the loss spectrum may be shifted.

©2007 Optical Society of America

OCIS codes: (060.2280) Fiber optics and optical communications: Fiber design and fabrication; (060.2400) Fiber optics and optical communications: Fiber properties

References and links

1. P. St. J. Russell, "Photonic-crystal fibers," *J. Lightwave Technol.* **24**, 4729-4749 (2006).
2. R. F. Cregan, B. F. Mangan, J. C. Knight, T. A. Birks, P. St. J. Russell, P. J. Roberts and D. C. Allan, "Single-mode photonic band gap guidance of light in air," *Science* **285**, 1537-1539 (1999).
3. C. M. Smith, N. Venkataraman, M. T. Gallagher, D. Müller, J. A. West, N. F. Borrelli, D. C. Allan and K. W. Koch, "Low-loss hollow-core silica/air photonic bandgap fibre," *Nature* **424**, 657-659 (2003).
4. B. J. Mangan, L. Farr, A. Langford, P. J. Roberts, D. P. Williams, F. County, M. Lawman, M. Mason, S. Coupland, R. Flea, and H. Sabert, "Low loss (1.7 dB/km) hollow core photonic bandgap fiber," *Conf. on Optical Fiber Communications*, (LA, USA, 2004), paper PDP24.
5. F. Couny, F. Benabid and P. S. Light, "Large-pitch kagome-structured hollow-core photonic crystal fiber," *Opt. Lett.* **31**, 3574-3576 (2006).
6. A. Argyros and J. Pla, "Hollow-core polymer fibres with a kagome lattice: potential for transmission in the infrared," *Opt. Express* **15**, 7713-7719 (2007).
7. T. D. Hedley, D. M. Bird, F. Benabid, J. C. Knight, P. St. J. Russell, "Modelling of a novel hollow-core photonic crystal fibre," paper QTuL4 in Proc. QELS, Baltimore MA (June 1-6, 2003)
8. J. M. Pottage, D. M. Bird, T. D. Hedley, T. A. Birks, J. C. Knight, P. St. J. Russell and P. J. Roberts, "Robust photonic band gaps for hollow core guidance in PCF made from high index glass," *Opt. Express* **11**, 2854-2861 (2003).
9. T. A. Birks, F. Luan, G. J. Pearce, A. Wang, J. C. Knight and D. M. Bird, "Bend loss in all-solid bandgap fibres," *Opt. Express* **14**, 5688-5698 (2006).
10. M. Koshiba and Y. Tsuji, "Curvilinear hybrid edge/nodal elements with triangular shape for guided-wave problems," *J. Lightwave Technol.* **18**, 737-743 (2000).
11. A. Nicolet, S. Guenneau, C. Geuzaine, and F. Zolla, "Modelling of electromagnetic waves in periodic media with finite elements," *J. Comp. Appl. Math.* **168**, 321-329 (2004).
12. F. L. Teixeira, and W. C. Chew, "General closed-form PML constitutive tensors to match arbitrary bianisotropic and dispersive linear media," *IEEE Microwave Guid. Wave Lett.* **8**, 223-225 (1998).
13. S. G. Johnson, M. Ibanescu, M. Skorobogatiy, O. Weisberg, T. D. Engeness, M. Soljacic, S. A. Jacobs, J. D. Joannopoulos and Y. Fink, "Low-loss asymptotically single-mode propagation in large-core OmniGuide fibers," *Opt. Express* **9**, 748-779 (2001).
14. L. Zschiedrich, S. Burger, R. Klöse, A. Schädle and F. Schmidt, "JCMmode: an adaptive finite element solver for the computation of leaky modes," *Proc. SPIE* **5728**, 192-202 (2005).
15. P. J. Roberts, D. P. Williams, B. J. Mangan, H. Sabert, F. Couny, W. J. Wadsworth, T. A. Birks, J. C. Knight and P. St. J. Russell "Realizing low loss air core photonic crystal fibers by exploiting an antiresonant core surround," *Opt. Express* **13**, 8277-8285 (2005).

1. Introduction

A photonic crystal fibre is a form of optical fibre, usually invariant along its length but possessing two-dimensional microstructure in the plane perpendicular to its axis [1]. This microstructure can lead to the existence of two-dimensional photonic bandgaps which, if they are sufficiently deep to cross the air-line (defined by $\beta=k_0$ for axial wavevector component (propagation constant) β and normalised frequency $k_0=2\pi/\Lambda$), can allow the guidance of light in hollow cores [2, 3].

Most hollow-core bandgap-guiding fibres are fabricated from silica glass, and comprise a honeycomb lattice with a large air-filling fraction (typically >80%), which surrounds and confines light within an air core. In such fibres, losses as low as 1.7 dB/km have been achieved [4]. However, recent results have demonstrated the favourable properties of a different structure of hollow-core PCF: the kagome fibre. Kagome fibres show broad optical transmission bands with relatively low loss, and have been reported to show no evidence of surface-mode crossings [5]. They have also been proposed as an ideal structure to reduce the large material losses in polymer PCFs [6]. However, although there are various suggestions as to the guidance mechanism in these fibres (such as low cladding density of states [1,7], low overlap between core and cladding mode fields [6] and high-order bandgaps [5]), the nature of guidance in these fibres is not fully understood.

In this paper, we demonstrate by numerical simulation that air-silica kagome fibres of the type described in Ref. [5] do not show photonic bandgaps in the frequency ranges measured experimentally. The low loss in kagome fibres therefore cannot be a result of bandgaps, making kagome fibres intrinsically different from bandgap-guiding hollow-core fibres. To understand the different behaviour of kagome fibres, we develop two models that can be understood more easily than the full kagome structure while retaining its key characteristics. One model is that of concentric hexagonal annuli, created by selectively omitting struts from a kagome lattice; and the other model is a related but simpler structure consisting of circular rings. We show that the variation of loss with wavelength of these models shares many characteristics with kagome fibres. Although such models cannot provide a complete explanation for the guidance of kagome fibres, they nevertheless provide a useful basis for understanding many features of their behaviour.

2. Density of states

The photonic density of states (DOS) is a convenient tool for presenting and examining the optical properties of a PCF cladding, including the existence and/or absence of photonic bandgaps over a relevant frequency range, and the identification of resonant features which can play an important role in determining guidance properties [8,9]. In this section we present and analyse the calculated density of states of a typical air-silica kagome cladding.

As an example structure, we consider an infinitely-periodic kagome array with glass refractive index $n=1.45$, strut width $d=0.67 \mu\text{m}$ and pitch $\Lambda=11.8 \mu\text{m}$. These parameters approximately reproduce the cladding of the '1 cell' fibre fabricated by Couny et al. [5] and are also similar to those reported by Argyros [6]. Figure 1(a) shows the kagome lattice. In order to calculate the density of states of this lattice, we use the finite-element method (FEM) with vector basis functions [10] in a fixed frequency formulation (i.e. obtaining β values as eigenvalues at a chosen k_0), and apply Bloch boundary conditions to the unit cell [11]. The resulting density of states is shown in Fig. 1(b).

Several features are evident in the DOS of the kagome structure. The near-vertical modes, extending both above and below the air-line [one example picked out with a dashed yellow line in Fig. 1(b)], are modes of the glass struts. Below the air-line these are leaky, but they retain their character over the range of β shown. Resonances of the air holes of the structure occur at particular values of the transverse wavevector in air (given by $k_t^2=k_0^2-\beta^2$), and these appear as horizontal lines on Fig. 2(b) which, as expected, exist only below the air-line. The first-order resonance of the hexagonal holes is picked out with a dotted yellow horizontal line in Fig. 2(b). Another feature of note in the DOS is the existence of a thick crossing region

surrounding the resonances at 0.7 and 1.4 μm , indicating that between each transmission band there is also a relatively broad region in which strong coupling between the core-guided mode and the glass strut modes might occur. Such behaviour is in agreement with previously published transmission spectra for kagome fibres [5, 6] and with the analysis of Argyros [6].

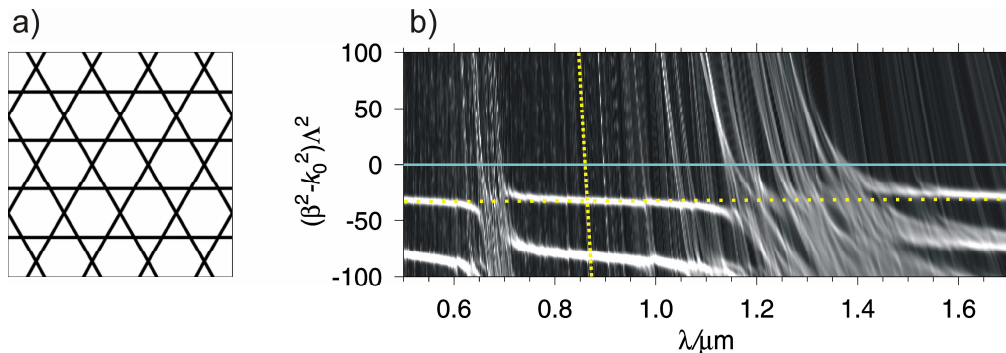


Fig. 1. (a). Periodic kagome lattice as described in Sec. 1, where black areas represent silica and white areas represent air. (b) Density of states (DOS) for the periodic kagome structure corresponding to normalized frequencies in the range $k_0\Lambda=44-148$. White regions show high DOS and darker areas show lower DOS, but the density of states is non-zero throughout. The solid horizontal line is the air line, the dashed near-vertical line is an example strut mode, and the dotted horizontal line is a mode associated with the large hexagonal air holes of the structure.

Although the density of states demonstrates that the kagome fibre does not achieve low-loss broad-band guidance through the existence of photonic bandgaps, and its features can be understood relatively simply, it is necessary to consider the full structure of a fibre in order to understand guidance completely. In the following section, two simplified models are considered as approximations to a real kagome fibre.

3. Concentric hexagon and ring models

To investigate the guidance in kagome fibres, we consider two approximations to the kagome structure. The first of these, most closely related to the kagome structure, is a set of concentric hexagonal annuli, which can be obtained by selectively omitting struts in the kagome structure as shown by Figs. 2(a) and 2(b). The second model, shown in Fig. 2(c), is a simple approximation to the first, in which the hexagons are replaced by concentric circles. We choose to use the same perimeter around each ring in the two models, the same thickness of glass and the same refractive indices. This has the effect of conserving the total amount of glass and leaving the positions of radial resonances (see below) unchanged.

To determine the modes of the concentric hexagon model, we use the FEM incorporating perfectly matched layers [12]. Although this method could also be used to calculate the modes of the concentric ring model, we instead choose to calculate these modes semi-analytically using transfer matrices in cylindrical coordinates [13]. The transfer matrix approach is not only orders of magnitude faster than the FEM, but also provides a useful check on the convergence and accuracy of the other models. Figure 3 shows the results of these calculations. In the case of both models, we select the fundamental mode guided in the air core and plot the loss of this mode as a function of wavelength. It is evident that there is a close similarity between the losses of the concentric rings and hexagons. The only major difference in the losses is an increase in ‘noise’ in the hexagonal model, which can be ascribed to the increased number of weak anti-crossings which were forbidden by symmetry in the circular case. This is a consequence of the sharp corners inherent in the hexagonal model which couple together several strut modes, allowing them to interact with the core-guided mode.

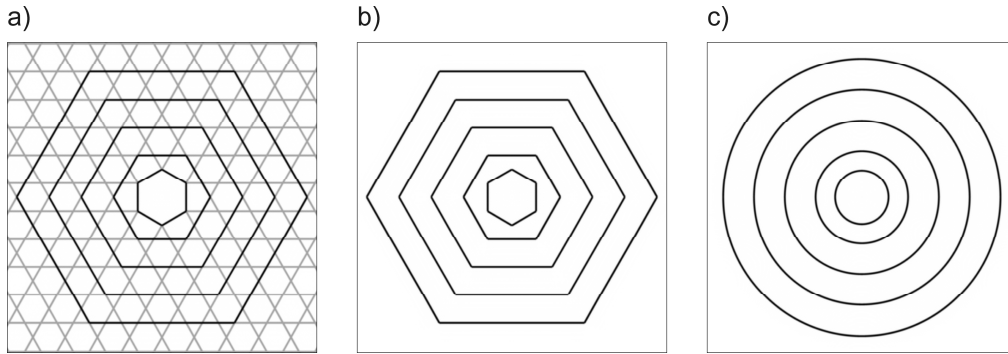


Fig. 2. (a) A 'full' kagome structure, with single cell core. The hexagons shown in (b) are highlighted in black. (b) The hexagonal approximation to the full kagome structure, obtained by retaining struts that contribute to concentric hexagons around the core but omitting all others. (c) The circular approximation to the hexagonal structure, formed of concentric circles that conserve the perimeter of each hexagon (thereby conserving the amount of glass). In (b) and (c) only the core and first four cladding rings are shown.

The features common to the ring and hexagon spectra regardless of the number of rings/hexagons are the high-loss resonant regions at approximately $\lambda=0.7 \mu\text{m}$ and $\lambda=1.4 \mu\text{m}$. The origin of these features is easily explained in terms of radial resonances of the glass comprising the rings/hexagons. Such resonances are expected for values of the transverse wavevector k_t such that $k_t t$, the phase change across a thickness t , is a multiple of π . Assuming the mode is on the air line, and hence $\beta=k_0$, this leads to a condition for resonance of $\lambda=2t(n^2-1)^{1/2}/m$ for integer m . Using $n=1.45$ and $t=0.67 \mu\text{m}$ correctly reproduces $\lambda=1.4, 0.7, \dots \mu\text{m}$.

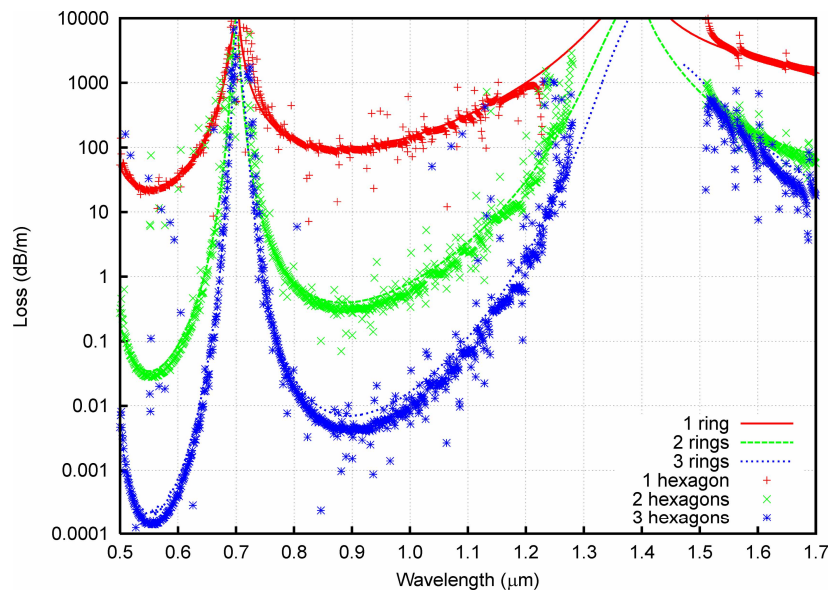


Fig. 3. Losses in dB/m for the fundamental mode of the ring (lines) and hexagon (points) models, with structures as shown in Fig. 2. Note the close agreement between the losses of the ring and hexagon models.

It is important to note from Fig. 3 that the concentric structures both show decreasing losses as the number of rings/hexagons is increased. This is a similar effect to the reduction in loss as

the number of layers of cladding in a bandgap-guiding PCF is increased [1], and in this case is the result of a ‘radial’ stop-band similar to that observed in Bragg fibres [13]. Although the resonances do not exactly match the edges of the previously measured loss spectrum, the simple expression derived above also indicates how sensitive the resonances (and corresponding loss windows) are to variations in strut thickness.

4. Comparison with kagome structure

In order to study guidance in realistic kagome structures, we used the FEM to calculate the loss of the fundamental air-guided mode in two- and four-layer structures. Figure 4 shows the two-layer structure. The loss of the two-layer structure was calculated with the FEM with perfectly matched layers. For the calculation of modes in the more computationally demanding four-layer structure, we used the commercial FEM package JCMmode with fourth-order edge elements, adaptive grid refinement, and adaptive transparent boundary conditions. This allows computation of losses to a high precision even for relatively large and complicated geometries [14]. In both cases, the relevant mode was selected by evaluating the fraction of power in the core of the fibre and choosing the mode that maximises this fraction.

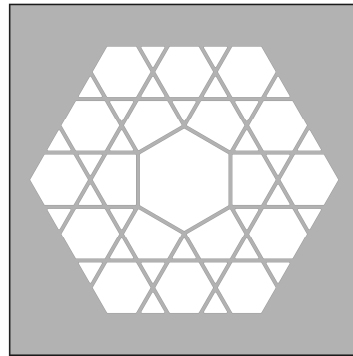


Fig. 4. Two-layer kagome structure used for modal calculations. Grey areas represent glass and white areas represent air. The dimensions are identical to those described in Sec. 2. In order to approximate real kagome fibres as closely as possible, the sharp edges in the structure are rounded with a radius of curvature of $0.2\ \mu\text{m}$.

A plot of the fibre losses, together with (for comparison) the curves for the one- and two-ring models, is given in Fig. 5. It is immediately clear that the resonances at $\lambda=1.4, 0.7, \dots\ \mu\text{m}$ are present in the spectra for the kagome fibre as well as that of the rings. This suggests that in fabricated structures it should be possible to tune the positions of low-loss regions by modifying the thickness of the struts in the kagome cladding. However, it should be noted that the resonances will broaden if there is inhomogeneity in the strut thicknesses throughout the structure, and this effect is likely to be more pronounced close to the core where the fields are more intense. To minimise loss it is therefore important to ensure that the structure comprises struts of a uniform width, including those struts surrounding the core. We note that this is a different requirement for low loss than that in bandgap-guiding hollow-core fibres [15].

The behaviour of the loss of the kagome structure with the spatial extent of the cladding is different from that of the rings/hexagons. While adding an additional hexagon or ring reduces the loss by approximately two orders of magnitude (as shown in Fig. 3), the two- and four-layer kagome structures both show remarkably similar losses. This suggests that light in the cladding is able to propagate freely away from the core. However, this is not unexpected: Fig. 1 demonstrates that the kagome structure does not have photonic bandgaps, and consequently propagation is not forbidden in the cladding.

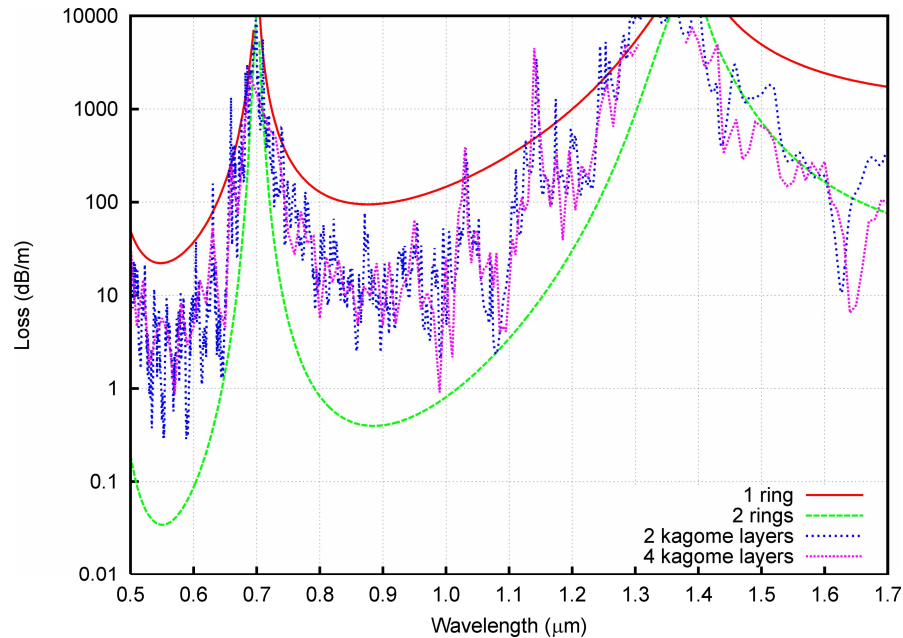


Fig. 5. Loss of the fundamental mode of the two- and four-layer kagome structures, together with that of the one- and two-ring models for comparison. Note the existence of high-loss resonances in the spectra for both the model and the realistic structures.

Because Fig. 3 suggests that concentric hexagons are able to achieve very low loss guidance, the much greater minimum losses of the realistic structure shown in Fig. 5 (at 0.55 μm and 0.9 μm) must be a result of the inclusion of the remaining struts that are neglected by the hexagon model. However, the high-loss resonances are common to both structures. It is therefore reasonable to suggest that there is a constant loss of approximately 10 dB/m in both kagome structures associated with coupling out of the core induced by the neglected struts, and this is superimposed on a background of losses associated with the radial confinement. Further study of the strut-induced coupling out of the core is likely to be key to further reductions of losses in kagome fibres.

5. Conclusions

We have demonstrated that models consisting of concentric rings and hexagons explain the qualitative features in the loss curves associated with kagome-structured PCF. Although these models are not quantitatively accurate, they provide a framework in which to understand and therefore control the positions of high-loss spectral features. Additionally they demonstrate that radial confinement is an important feature of guidance in kagome fibres, which consequently implies that the fabrication of kagome fibres with a uniform strut thickness throughout is likely to provide guidance with lower loss.

Although radial confinement is an important component of the guidance mechanism in kagome fibres, the losses observed in realistic fibres (which we have calculated accurately using the FEM) are dominated by coupling out of the core, which must be a result of the struts that are neglected in our simplified models. To obtain accurate calculations of losses in kagome fibres, it is therefore essential to take into account the full structure and use a rigorous method such as the FEM. Further consideration of the effect of these struts is likely to be beneficial in advancing understanding of guidance in kagome PCF.