Application of Full-Wave Electromagnetic Solvers to Micro/Nano-structured Fibres

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Abstract
The progress of full-field electromagnetic tools coupled to increasingly powerful computing hardware offer the possibility of modelling accurately micro/nano-structured fibres. Together with the advances in fabrication methods, this opens the door to the realization of optimized designs with growing complexity. Three examples of simulations are presented here to illustrate the application of general-purpose electromagnetic solvers to the analysis of micro/nano-structured fibres. Using appropriate numerical tools, the mode propagation in a fibre, the optimised coupling into a fibre from an incident field distribution, and the near-field diffraction patterns from a fibre tip can be characterized.

Keywords: Numerical analysis; sub-wavelength; micro/nano-structured fibre; computational electromagnetics

Introduction
Micro/nano-structured optical fibres (M/NOFs) with sub-wavelength features have attracted attention in optics and terahertz [Atakaramains *et al.* 2008; Hu *et al.* 2009]. Depending on the application, these fibres can be designed to provide properties such as tight mode confinement, low loss, strong field enhancement on the air-material discontinuities, low waveguide dispersion, enhanced nonlinearity, and strong birefringence for the preservation of polarization [Wang *et al.* 2008]. Traditionally semi-analytical or high-frequency asymptotical methods have been used for the modelling of conventional optical fibres, where the dimension of fibre was typically larger than the operating wavelength [Xu *et al.* 2000]. The progress in fibre fabrication techniques has allowed the design and realization of sub-wavelength structures for THz and optics. Such complex inhomogeneous structures require solving the full vectorial form of Maxwell's equations which requires full-wave electromagnetic (EM) simulations. Moreover, the continuing advances in the development of EM numerical analysis methods for radio-frequency devices and the development of computing hardware have expanded the capability of EM simulation tools for solving large and complex problems. Therefore, full-wave EM solvers are becoming indispensable tools for the design and analysis of M/NOFs. Here we explain the capability of two/three dimensional EM Solvers in tackling problems such as guiding properties, optimal coupling into the fibre and analysis of the diffraction patterns from the fibre end-tip for sensing and imaging purposes.

Two-dimensional (2D) Eigenmode Analysis
Full-vector analytical solutions only exist for extremely simple fibre design (such as, e.g., a circular core embedded in an infinite cladding), and can not be found in general for M/NOFs such as THz porous fibres (TPFs) and photonic crystal fibres (PCFs). Thus numerical approaches can provide a powerful alternative for the design and study of their guiding properties. Eigenmode analyses are typically performed with solvers based on the finite-difference method (FDM) or the finite-element method (FEM). Both approaches can provide highly accurate solution for the propagation constant, cut-off frequency, confinement loss and birefringent properties of waveguides. For M/NOFs, such eigenmode solvers have been applied especially for PCFs and compared in terms of usefulness and limitation [Zhu *et al.* 2002; Saitoh *et al.* 2005; Ademgil *et al.* 2008].
As an example of the application of an eigenmode solver, the guiding properties of TPFs have been studied using the FEM package COMSOL [Atakaramains *et al.* 2008]. The cross-section of a TPF is shown in Fig. 1(a). The eigenvalue problem is formed by applying variational equations to each of the 2D finite-elements used to discretize the fibre profile as shown in Fig. 1(b). Applying the proper boundary conditions the guiding properties (e.g. effective material loss, α_{eff}, and effective refractive index, n_{eff}, as shown in Figs. 1(d) & 1(e) respectively) and field distribution (shown in Fig. 1(c)) can be calculated. It should be noted that 2D numerical methods suffice for design and study of the guiding properties of M/NOFs, provided that there is no variation in the longitudinal direction, i.e. the waveguides can be considered to be of infinite length.

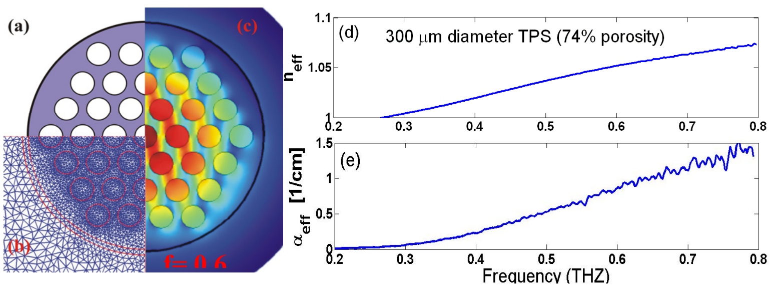

Figure 1: (a) Geometry, (b) FEM elements, (c) field distribution, (d) n_{eff} and (e) α_{eff} of a TPF. After Atakaramains *et al.* (2008).

Three-dimensional (3D) EM Solvers

The modal properties obtained from an eigenmode analysis can be exploited in the beam propagation method (BPM) to compute the propagation constants of longitudinally varying M/NOFs. This approach is efficient and accurate for analysing the propagation in fibres with slowly varying profiles [Saitoh *et al.* 2005]. Nevertheless, it is based on approximations that generally neglect reflected waves. Thus, full-field EM solvers are better suited for the investigation of fibre problems involving reflection, diffraction and scattering effects. Among the methods traditionally used for this purpose, the FEM, the Finite-Difference Time-Domain (FDTD) method, or the Boundary Element Method (BEM) are notable examples. For example, FDTD has been applied to compute the propagation of pulses in M/NOFs [Hu *et al.* 2009], the near/far-field output for fibres with flat, angled, spherical and tapered end-faces [Wang *et al.* 2008]. In the following, the application of two different EM solvers is discussed for the investigation of typical discontinuities of M/NOFs, i.e. the coupling from an incident beam into an M/NOF, and the near-field diffraction pattern emerging from the end of an M/NOF.

Optimal power coupling into the M/NOFs – 3D EM solvers can be useful tools in optimising different parameters to achieve maximum coupling into M/NOFs, where the weekly guidance approximation formula fails. The coupling of power into a fibre is modelled here using the frequency-domain FEM package Ansoft HFSS. It is worth mentioning that the power coupled into the propagating mode needs to be computed at a sufficient distance from the discontinuity to make sure that radiation modes are suppressed. As the modelling of a very long fibre segment is not computationally efficient, a mode projection technique [Baumann *et al.* 2005] will need to be applied to guarantee that accurate results, even when a short length of the fibre is modelled. Fig. 2 shows the normalised power in a THz single-mode solid-core fibre (at 1.5×Rayleigh range distance from the source) as a function of beamwidth, for an incident Gaussian input profile. Results can be refined after applying the mode projection.

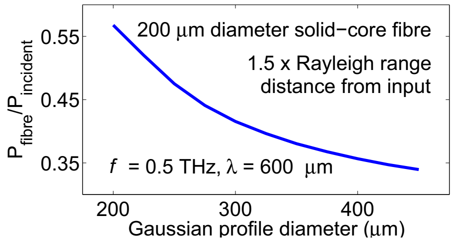

Figure 2: Near-field coupling from a Gaussian profile into the fibre.

Diffraction from the end-tip of M/NOFs – The far-field quantities can be calculated based on the propagating fibre mode distribution using the surface equivalence theorem and Green functions. For sensing and imaging applications, it is important to understand the spatial structure of the near-field pattern as well. In contrast to the far-field, the near-field is very challenging to characterize. Fig. 3 shows the diffracted field distribution from a spider-web TPF end-tip [Atakaramains *et al.* 2008] as obtained in the near-field using an in-house code based on the Finite-Volume Time-Domain (FVTD) method [Baumann *et al.* 2005]. Time-domain methods can be advantageous over frequency-domain approaches, as they can, in principle, tackle nonlinear behaviours [Hu *et al.* 2009]. Additionally, the unstructured tetrahedral discretization of the FVTD method grants a geometrical flexibility required to model accurately M/NOFs. Fig. 3 shows (a) the fibre-tip model, (b) the obtained field distribution of the propagating mode (which shows the high field intensity within the voids) and, (c) the field distribution at 8 μm distance from the fibre tip. It can be seen how the features of the propagating modes are getting blurred over a very short distance.

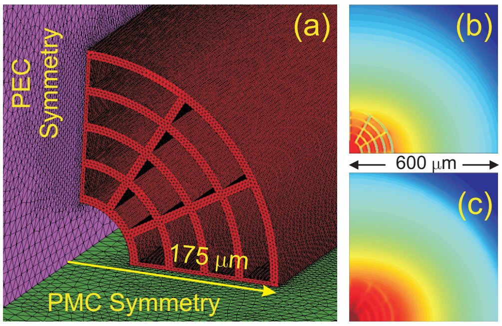

Figure 3: (a) Skin mesh of the fibre tip. Transverse E-field at 0.45 THz (b) at the fibre tip, and (c) at 8 μm after the fibre.

Conclusion

We demonstrate three examples of full-field EM solvers application to M/NOF problems. Three different tools have been used for calculating the guiding properties of a TPF, optimizing the coupling into a solid-core fibre, and determining the near-field diffraction from the end-tip of a spider-web TPF with sub-wavelength features.

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