OptiSystem

Optical Communication System
and Amplifier Design Suite

Air-hole Assisted Multicore Fiber

Applications

- Space division multiplexing (SDM) communication systems
- Different multicore fiber (MCF) design and analysis:
  - Single-mode and few-mode per core
  - Trench-assisted and/or hole-assisted cores
  - Step and graded index refractive index profiles
  - Crosstalk, leakage loss and bending loss analysis
  - Effective area and core multiplicity factor
  - Dispersion and differential group delay analysis

Overview

SDM using few-mode and multicore fibers (MCFs) is widely investigated to overcome the capacity limitation of conventional single mode fibers currently deployed.
MCFs can be manufactured with different refractive index profiles, with/without trench, with/without air-hole structures and in large diverse layouts [1]. The key performance parameters and design criteria of MCFs include inter-core crosstalk, leakage and bending losses, bandwidth and effective area. Multicore fibers are typically designed and simulated using the finite element method (FEM). Optiwave has developed *MCF* components in OptiSystem software to facilitate seamless design and analysis of MCFs using parameters extracted from the vector FEM mode solver in OptiMode software. SDM transmission systems can be designed and simulated in OptiSystem software.

OptiSystem Software Features

- Rapid prototyping of complex optical systems using extensive libraries of optical components
- Dedicated SDM library with built-in generic MCF and multimode MUX/DEMUX components
- Comprehensive optical fiber propagation models
- Temporal, spectral and spatial signal visualization capabilities

OptiMode Software Features

- Includes accurate and fast vector FEM mode solver.
- Supports triangular mesh that can be adapted to accurately approximate fine geometry features, refractive index profile and electromagnetic fields.
- Uniaxial perfectly matched layer (UPML) boundary condition enables identification of leaky modes.
- MCF bending loss can be accurately analyzed using transformation optics.
- Built-in VBScript capabilities accelerate the design and optimization of complex MCF profiles.
- Exploiting the symmetric boundary conditions reduces the simulation domain, and modes of certain symmetry can be readily targeted.
- Supports lossy, dispersive and anisotropic materials in full vector formulation.
- Supports accurate and spurious-solution proof higher order hybrid vector/nodal elements.
- Specific modes can be targeted through a user-specified complex modal effective index estimate.

Simulation Description

The design and analysis of six-core air-hole assisted multicore fiber proposed in [2] is conducted using OptiMode software. The design is depicted in Fig. 1, where each step-index single-mode core (radius: *a*=5μm and index contrast of Δ=0.35%) is surrounded by six air-holes to suppress both inter-core crosstalk and leakage losses. The cores and air-holes are placed on the vertices of a hexagon with sides of *D* and *Λ*, respectively. A 125μm diameter silica cladding coated by a jacket with refractive index of 1.45 surrounds the cores.

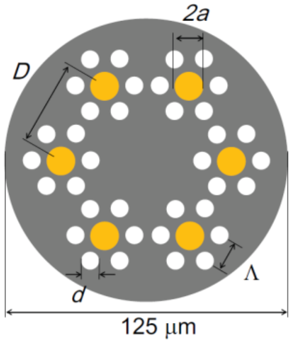

Figure 1: Schematic of six-core air-hole assisted MCF [2].

Utilizing the built-in scripting capabilities of OptiMode software, the MCF layout can be easily realized using a nested "*For Loop*" that rotates copies of the core/air-hole. User-defined variables known as ***parameters*** are another powerful feature of the Design environment. These *parameters* can be used in mathematical expressions to define other variables, to parameterize the layout elements such as an air-hole location or size, to set the simulation domain size, to perform automated parameter sweeps and design optimization. The parameters are also fully accessible within the script. Combining these features in a parameterized and scripted layout makes any subset of design parameters easily studied by a few clicks within the GUI.

The MCF structure shown in Fig. 1 is designed and analyzed using OptiMode. The used FEM mesh of modal analysis for a straight MCF is illustrated in Fig. 2. A symmetric boundary condition is set along the horizontal axis halving the simulation domain. The inter-core crosstalk, leakage loss and bending loss of the structure are calculated.

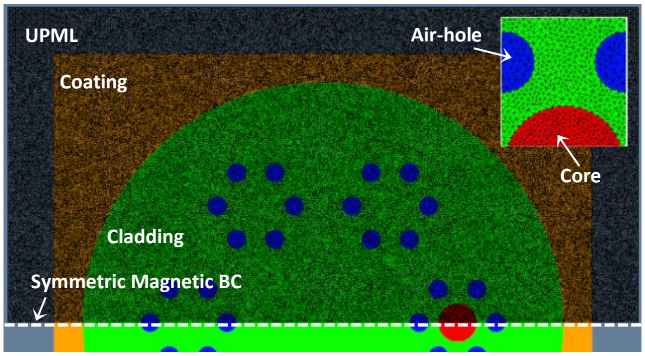

Figure 2: Simulation domain with the FEM mesh superimposed. Inset shows a zoomed view close to the core and air-hole boundaries.

The vector electric & magnetic fields and modal indices obtained in a 2-level parameter sweep for a core pitch (*D*) and air-hole diameter (*d*) (see Fig. 1) are exported and post processed to calculate the field coupling coefficients required to evaluate the crosstalk based on the coupled power model [3]. Calculated inter-core crosstalk assuming a bending radius of 85mm is shown in Fig. 3.

OptiMode can accurately calculate the bending and leakage losses of the MCF using conformal mapping of the bent waveguide to an equivalent straight waveguide with graded anisotropic material combined with a UPML boundary condition. Fig. 3 also shows the leakage loss of the bent MCF due to combined effects of finite cladding size and bending (R_{bend}=85mm). The simulation is conducted for the core placed furthest from the center of the curvature when the fundamental mode polarized within the bending plane (which incurs the highest loss). The calculated crosstalk and leakage loss using OptiMode match well with the simulation results of reference [2]. The simulated results using Optiwave software and the measured MCF results are compared in Table 1. The fabricated MCF in reference [2] has the following specifications: *a*=4.9μm, *D*=31.6μm, Λ=10μm, *d*=6.0μm.

The core-averaged core-core crosstalk, core modal effective area and cut-off wavelength of the 2nd order mode (LP_{11}) parameters are in close agreement with the measured values in reference [2]. Fig. 4 shows the simulated macro-bending characteristics of the fabricated MCF at 1.625μm wavelength for the furthest cores from the center of curvature with highest and lowest bend loss. These results are comparable to the measurements in reference [2].

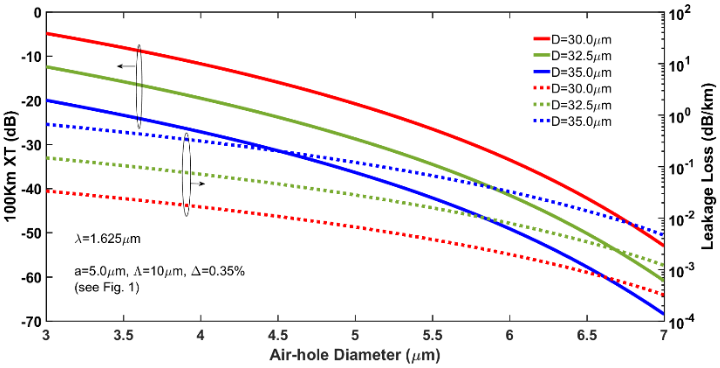

Figure 3: Average core-core crosstalk and leakage loss (worst case) of the MCF shown in Fig. 1 as a function of air-hole diameter when core pitch=30,32.5 and 35μm for bending radius of 85mm. (solid curve for crosstalk, dashed curve for loss)

Table 1. Comparison of measured [2] and simulated MCF characteristics in Optiwave software.

Core Averaged Value	*A_{eff} (μm^2) λ=1.55μm*	*Crosstalk (dB/Km) λ=1.625μm*	*$\lambda_{cut\text{-}off}$ (nm)*
Measured [2]	*72.7*	*-55.50*	*1390*
Optiwave Simulation	*72.4*	*-55.48*	*1387†*

†Calculated for LP_{11} bending loss>1dB/m at R_{bend}=140mm

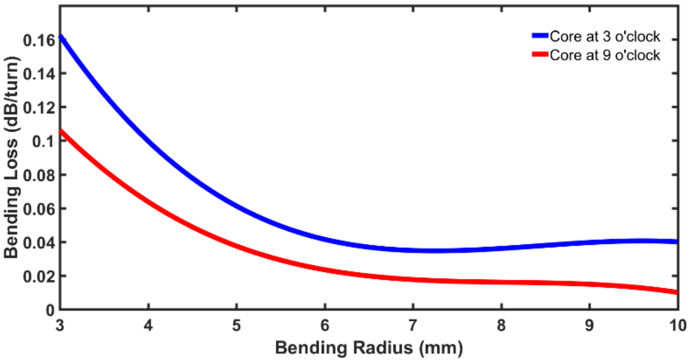

Figure 4: Calculated Macro-bending loss of the fabricated MCF shown in Fig. 1 as a function of the bending radius, for the cores furthest from (3 o'clock) and closest to (9 o'clock) the center of curvature.

References

[1] K. Saitoh and S. Matsuo, “Multicore Fiber Technology,” J. Lightwave Technol. **34**, 55-66 (2016)

[2] T. Sakamoto, K. Saitoh, N. Hanzawa, K. Tsujikawa, L. Ma, M. Koshiba, and F. Yamamoto, “Crosstalk suppressed hole-assisted 6-core fiber with cladding diameter of 125 μm,” Eur. Conf. Opt. Commun., (ECOC 2013), Paper Mo.3.A.3.

[3] M. Koshiba, K. Saitoh, K. Takenaga and S. Matsuo, “Analytical Expression of Average Power-Coupling Coefficients for Estimating Intercore Crosstalk in Multicore Fibers,” IEEE Photonics Journal, **4**, 1987-1995 (2012).