Optiwave

OptiMode
Waveguide Modal Analysis Software

Photonic Crystal Fiber Temperature Sensor

Applications

- Chemical and environmental sensors
- Bio-medical sensors
- Particle trapping
- Nonlinear optics
- High-power beam delivery
- Extreme dispersion values
- Endlessly single-mode fibers
- Sub-wavelength optics
- Bent waveguides

OptiMode Software Features

- Includes a vector finite element method (VFEM), which is fast and accurate relative to other mode solving algorithms.
- Triangular mesh can be adapted to accurately approximate the fine features of the geometry, refractive index profile, and electromagnetic fields.
- Built-in VBScript capabilities accelerate the design and optimization of complex waveguide profiles.
- Exploiting the symmetric boundary conditions reduces the simulation domain, and modes of certain symmetry can be readily targeted.
- Full vector formulation for lossy, dispersive, and anisotropic materials.
- Uniaxial perfectly matched layer (UPML) enables identification of leaky modes.
- Accurate and spurious-solution proof higher order hybrid vector/nodal elements capabilities.
- Specific modes can be targeted through a user-specified modal index estimate.
- Accurate analysis of arbitrary bent waveguides using transformation optics.

Overview

Photonic crystal fibers (PCF) have been extensively investigated for chemical, bio-medical, and environmental sensing applications. PCF provides a unique platform for realizing the desired modal dispersion, birefringence, confinement, and multiplicity characteristics. This can be attributed to the freedom in designing the microstructure geometry. Of significant importance for sensing applications, various chemical, biological, and inorganic materials can be introduced by selective infiltration of the holes or using deposition techniques. PCF sensors often involve structural and electromagnetic field features that span multiple orders of magnitude in variation, e.g. sub-wavelength metal films supporting tightly confined surface plasmon modes in a PCF with mode areas, air-holes and cladding dimensions of 10s and 100s of wavelength, respectively. These properties require a mode solver that can both efficiently and accurately approximate the geometry and the electromagnetic fields over the entire simulation domain.

Simulation Description

The surface plasmon assisted PCF temperature sensor proposed in [1] is simulated in OptiMode software. The temperature variation in the sensor affects the phase matching between the core and the lossy plasmonic modes resulting in loss incurred by the fundamental mode. A triangular lattice with a pitch of 2µm for a silica PCF is depicted in Fig. 1. The central and 1st layer of the air-holes have diameters of 1µm and 1.2µm, respectively. The 2nd layer of holes (diameter=1.6µ) are filled with a temperature sensitive liquid (n_{Liq}=1.35 at 25°C) and selectively coated with a 40nm thick gold layer.

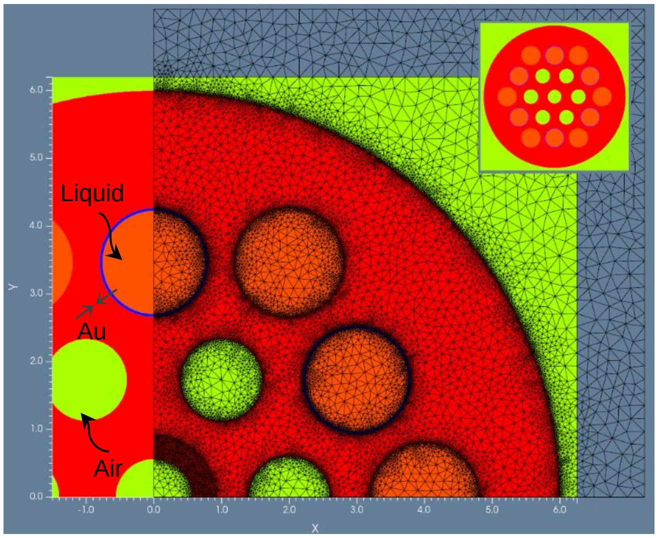

Figure 1: Schematic of the PCF (inset) and the actual simulation window with the FEM mesh superimposed.

Imposing the symmetric magnetic/electric boundary conditions along the X/Y axis in OptiMode reduces the simulation domain by a factor of 4. As shown in Fig. 1, the triangular mesh is configured to precisely represent both the sub-wavelength Au coatings and the hole boundaries. This mesh enables efficient modeling of both the surface plasmonic modes and the core modes with high accuracy.

VFEM solver in OptiMode is used to calculate the complex effective modal indices of both the core-guided and the plasmonic modes of the PCF at 25°C. The loss spectra of the fundamental mode, obtained from the imaginary part of the modal index, is shown in Fig. 2 (a). The Peaks in the loss spectra, marked on the figure and reported in Table 1, correspond to the phase-matched wavelengths where the dispersion relations of the core-mode and a plasmonic mode intersect, as shown in Fig. 2 (b).

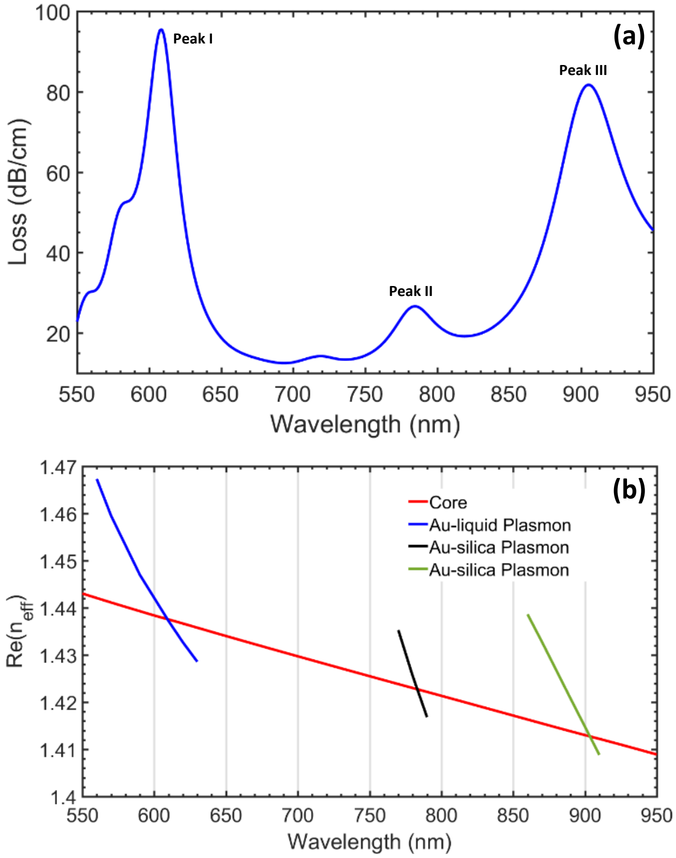

Figure 2: Modal analysis of the PCF at 25°C in OptiMode: (a) Loss spectra of the core-mode calculated from the imaginary part of the modal indices. (b) dispersion relation of the core the plasmonic modes.

Table 1: OptiMode calculated Peak-loss wavelengths at 25°C, as indicated in Fig. 2 and compared with Ref. [1].

λ (nm)	OptiMode	Peng *et al.* [1]
Peak I	608	608
Peak II	784	780*
Peak III	905	903

*estimated from Fig. 2 (b) in [1].

Strong wavelength dependant coupling between the core and the plasmonic modes is also evident in the electric field profiles depicted in Fig 3. Comparing the field profiles of an off-resonant wavelength, e.g. 700nm shown in Fig. 3 (b) with shorter and longer loss-peak wavelength depicted in Fig 3 (c) and Fig. 3 (d) respectively, a higher coupling is noticeable between the core mode and a plasmonic mode bonded to the Au (silica)-liquid interface. The corresponding modal indices calculated in OptiMode (presented in Table 2) are well matched with the reported values in Ref. [1]. Assuming a temperature dependant Sellmeier (Drude) model for the silica (gold), thermal sensitivity of -4x10^{-4}(°C^{-1}) for the liquid filling and thermal expansion of the gold coating as in Ref. [1], the temperature response of the PCF sensor was simulated in OptiMode and shown in Fig. 4.

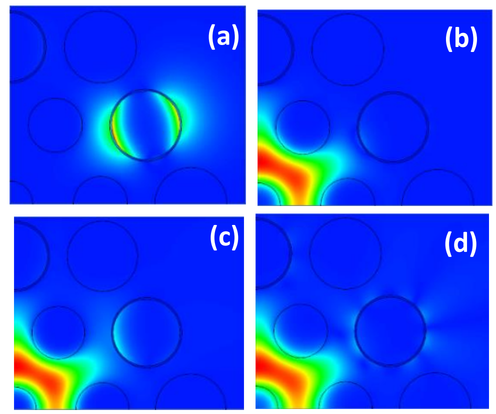

Figure 3: Electric-field amplitude profiles (|Ex|) at specified wavelengths: (a) Au-liquid interface bound plasmonic mode at 560nm and (b-d) X-polarized fundamental core mode at 700nm, Peak I and Peak III (see table 1 and Fig. 2), respectively.

Table 2: Modal indices of the fundamental core and Au-liquid interface bonded surface plasmon mode (SP_{Liq}) at selescted wavelenghts calculated in OptiMode and compared with Ref. [1].

Mode	λ (nm)	OptiMode	Peng et al. [1]
SP_{Liq}	560	1.4673+7.746e-3i	1.467+7.739e-3i
Core	608	1.4377+1.066e-4i	1.438+1.063e-4i
Core	700	1.4297+1.6280e-5i	1.430+1.627e-5i
Core	903	1.4126+1.355e-4	1.413+1.361e-4i

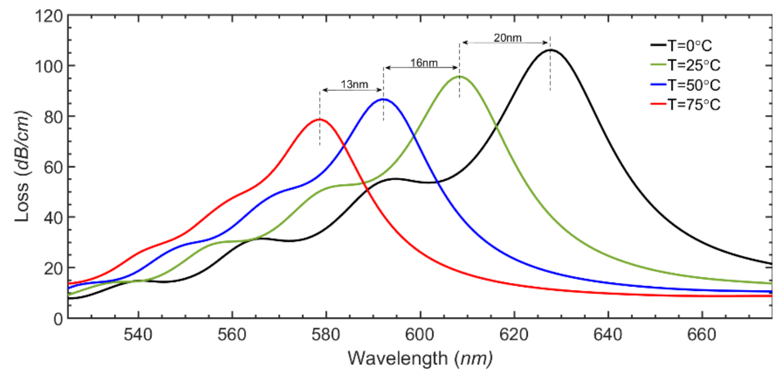

Figure 4: Loss spectra of the core mode of the PCF sensor (shortest wavelength peak-loss) at selected temperatures calculated in OptiMode.

References

[1] Y. Peng, J. Hou, Z. Huang, and Q. Lu, "Temperature sensor based on surface plasmon resonance within selectively coated photonic crystal fiber," Appl. Opt. 51, 6361-6367 (201 2).