OptiMode
Waveguide Modal Analysis Software

Photonic Crystal Fiber Bio-chemical Sensor

Applications

- Chemical, environmental, and biomedical sensors
- High-power beam delivery and nonlinear optics
- Endlessly single-mode fibers
- Extreme dispersion characteristics
- Sub-wavelength optics
- Particle trapping
- Bent waveguides

OptiMode Software Features

- OptiMode Includes a vector finite element method (VFEM) mode solver 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.
- Supports lossy, dispersive and anisotropic materials in full vector formulation.
- Uniaxial perfectly matched layer (UPML) boundary condition enables identification of leaky modes.
- Supports accurate and spurious-solution proof higher order hybrid vector/nodal elements.
- Specific modes can be targeted through a user-specified complex modal index estimate.
- Arbitrary bent waveguides can be accurately analyzed using transformation optics.

Overview

Photonic crystal fibers (PCF) are attractive for chemical, biomedical, and environmental sensing applications. The freedom in designing the microstructure geometry provides a unique platform for realizing the desired modal dispersion, birefringence, confinement and multiplicity characteristics. Of significant importance to these features, chemical, biological and inorganic materials can be introduced to the PCF by selective hole infiltration or deposition techniques. Novel PCF sensor designs often encompass structural and electromagnetic field features spanning multiple orders of magnitude in variation, e.g. sub-wavelength metal films and tightly confined surface plasmonic modes in a PCF with wavelength-scale mode and air-hole radii having cladding dimensions of 100 times of the wavelength. 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 interaction between core-confined and plasmonic modes in hybrid PCF-plasmonic waveguides can enhance the sensitivity of the bio-chemical and environmental sensors. Strong dependence of the dispersion characteristics of the plasmonic mode to the dielectric profile at the metal interface affects the phase matching between the modes and hence the loss incurred by the core mode. In the strong coupling regime, anti-resonant crossing manifested as a kink or an s-shaped transition in the dispersion relation in the vicinity of the phase-matched point may occur [1]. Besides the variation of the propagation loss, the resultant abrupt phase shift of the transmitted light enhances the sensitivity in polarimetric and phase-sensitive interrogation methods.

The surface plasmon resonance assisted D-shaped PCF proposed as a refractive index sensor in [2] and shown in Fig. 1 is simulated using OptiMode software. The D-shaped silica (n=1.45) PCF has a center air-hole and cladding diameters of 0.4μm and 1.6μm, respectively. All holes are arranged in a 2μm-pitch hexagonal lattice.

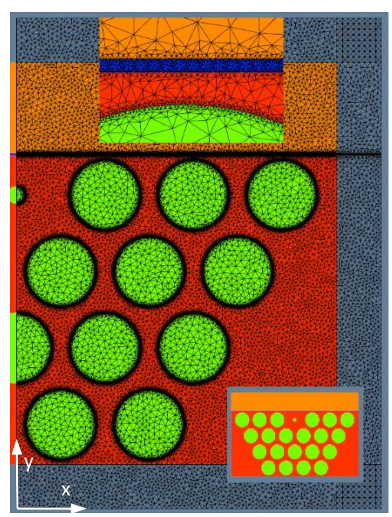

Figure 1: Simulation domain with the FEM mesh superimposed. (Lower inset) schematic of the PCF. (Top inset) a zoomed view of the mesh at the metal-dielectric interfaces and a hole boundary.

A 40nm-thick gold layer is deposited on the flat-polished cladding surface at a height of 0.9µm from the center of the fiber and an aqueous analyte with refractive index of n_a=1.33 to1.34 is introduced on the metal film.

The X/Y-polarized modes can be selectively simulated in OptiMode by imposing the symmetric magnetic (electric) boundary condition along the y-axis which also reduces the simulation domain by a factor of 2. As shown in Fig. 1, the triangular mesh is configured to precisely represent the sub-wavelength gold layer and the hole boundaries. This mesh enables efficient and accurate modeling of both the surface plasmon and the core modes.

VFEM solver in OptiMode software is employed to calculate the complex effective indices and the field profiles of the X- and Y-polarized modes of the waveguide. The X-polarized core mode, incapable of exciting the plasmon polaritons, retains the low-loss propagation, dispersion and field profile characteristics of an isolated guided mode as shown in Fig. 2 and 3, respectively. In contrast, strongly coupled Y-polarized core and surface plasmonic modes form symmetric (anti-symmetric) super-modes with anti-crossing signature at the phase-matched wavelength, shown as the upper (lower) dispersion bands in Fig. 2. As evident from the field profiles of Fig. 3 and at shorter wavelengths, the upper (lower) band represents the surface plasmonic (core) mode and vice versa at longer wavelengths. The field plots in Fig. 4 further illustrates the symmetric (anti-symmetric) nature of dispersion bands and the strong coupling of the modes at the phase- matched wavelength where the loss of the core-like Y-polarized mode peaks.

The PCF refractive index bio-sensor can be utilized in various interrogation schemes; namely, tracking the loss-peak wavelength with $S_\lambda = \Delta\lambda_{loss-peak}/\Delta n_a \sim 3300 \left[\frac{nm}{RIU}\right]$, monitoring the power at a fixed wavelength with peak sensitivity of $S_a = (\Delta\alpha/\Delta n_a)/\alpha_{n_a=1.33} \sim 135 \left[\frac{1}{RIU}\right]$ at 700nm

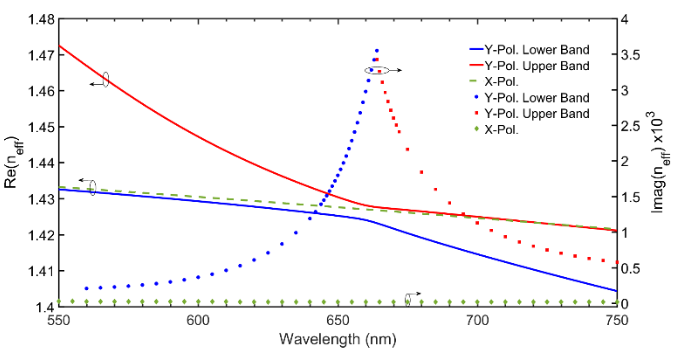

Figure 2: Complex modal indices of the D-shaped PCF calculated in OptiMode when analyte refractive index is 1.33.

wavelength, or utilizing the phase difference between the two polarizations of the core mode defined in normalized form as $\Delta\phi = \frac{2\pi}{\lambda} Re\left(n_{eff}^{y-pol} - n_{eff}^{x-pol}\right) \left[\frac{rad}{\mu m}\right]$, as depicted in Fig. 5 (a)-(c), respectively.

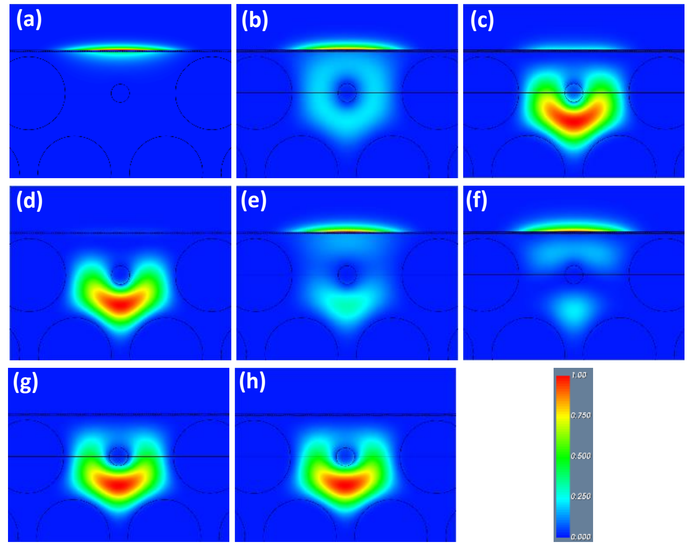

Figure 3: Electric-field intensity profile of, (a)-(f) y-polarized and (g)-(h) x-polarized modes from left to right at 560nm, 664nm and 750nm wavelength, respectively. Top (middle) row corresponds to the upper (lower) dispersion band in Fig. 2.

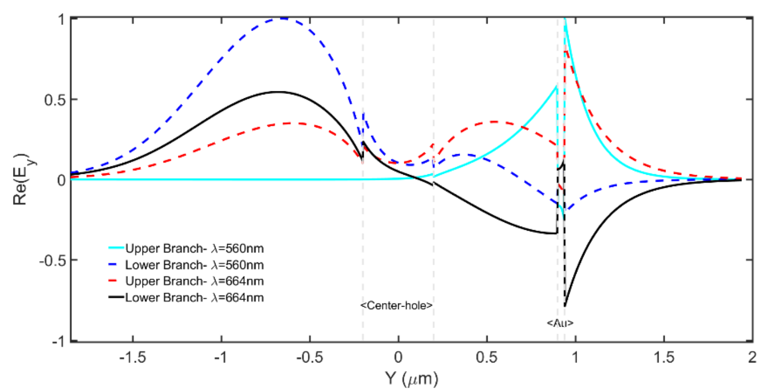

Figure 4: Electric field profile of the Y-polarized modes, real(E_y), along the y-axis at specified wavelengths (fields normalized to unit power and assuming n_a=1.33).

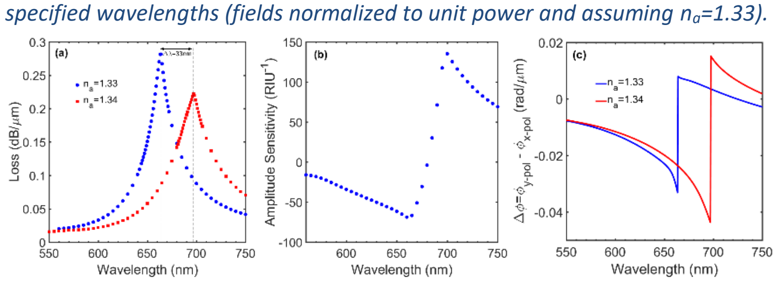

Figure 5: (a) Loss spectra and (b) the amplitude sensitivity of the Y-polarized core mode. (c) Phase difference between the y-polarized and X-polarized core modes.

References

[1] H. Ditlbacher, N. Galler, D. Koller, A. Hohenau, A. Leitner, F. Aussenegg, and J. Krenn, "Coupling dielectric waveguide modes to surface plasmon polaritons," Opt. Express 16, 10455-10464 (2008).

[2] N. Luan, R. Wang, W. Lv, and J. Yao, "Surface plasmon resonance sensor based on D-shaped microstructured optical fiber with hollow core," Opt. Express 23, 8576-8582 (2015).