Mode analysis of birefringent doped-core holey fibers

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Holey fibers (HF) as a subgroup of photonic crystal fibers (PCF) constitute a new class of optical fibers which has revealed many interesting phenomena paving the way for a large number of novel applications either in the telecom or in the sensing domain. However, some of the applications require the use of specialty fibers with a doped core. A numerical investigation of fundamental and higher order modes propagating in doped core birefringent holey fiber is presented. The conditions for the co-existence of two competing light guiding mechanisms, their consequences on the mode propagation and the potentialities for novel applications are discussed.

Introduction

The typical HF [1] consists of pure silica with a periodic distribution of air holes in the cladding. However, some of the applications require the use of specialty fibers with a doped core. The latter plays the role either of active region in fiber lasers and amplifiers [2] or as UV-sensitive region for writing fiber Bragg gratings [3]. Such a doped core holey fiber (DCHF) gives more opportunities for tailoring and designing the intensity distribution of the guided modes, which can be an asset of this type of HF with respect to the classical doped core step index fiber.

In this paper, we consider a DCHF with a microstructured cladding consisting of elliptical air holes of short axis length 2ρ and ellipticity e arranged in a hexagonal lattice with a pitch Λ, a doped circular core region with radius r_{dop} and a refractive index n_{dop} (Fig.1). The mode analysis for this fiber is performed using a numerical technique based on a full-vectorial mode solver, which is a frequency-domain method, and is based on solving numerically the eigenequation for the transverse field components and the propagation constant in a truncated orthonormal basis [4]. This approach allows the accurate modeling of the effective refractive indices of both cladding and guided modes, and to determine the number of modes and the mode intensity distributions.

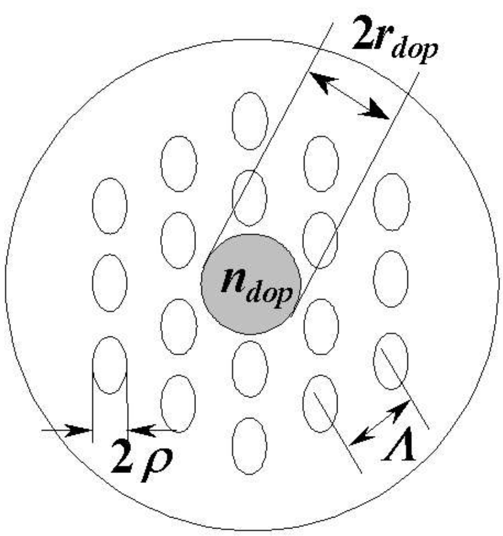


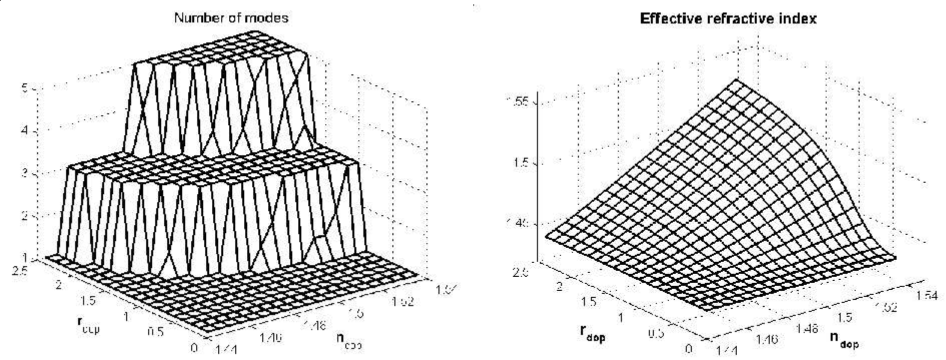
Figure 1. Structure of doped core holey fiber with ellipticity of holes e=2.

Propagation regimes in the DCHF

We have extensively modeled the mode distributions, effective refractive indices and the number of guided modes as a function of the two parameters that define the doped region of this DCHF (r_{dop} and n_{dop}). The results shown in Fig. 2 illustrate that with an increase of refractive index and radius of doped core, the number of modes and effective refractive indices are also increasing. Nevertheless, it is still possible for a relatively large area of our parameter space to achieve the single mode propagation through the doped core region without having to decrease its index of refraction.

Moreover, a doped core decreases the radius of the guided mode so that it responds stronger to the Bragg grating. Generally speaking, one may influence the shape and the distribution of the guided modes by altering all four above-mentioned parameters of the fiber.

If we assume that the DCHF is a superposition of two different types of fiber, namely the HF and the standard step index fiber (SIF), then we can distinguish two main guiding mechanisms.



A *B*

Figure 2. Number of modes (A) and effective refractive index of fundamental mode (B) in function of doped core radius (r_{dop}) and refractive index (n_{dop}). Simulations were done for the following structure: Λ=5μm, ρ=1μm and wavelength λ=1.55μm. Each of the modes on figure A stands for two polarization modes of DCHF.

These two guiding mechanisms help us to explain the propagation regimes of the DCHF indicated on Fig. 3. The first regime (I) allows the propagation of only one mode through the HF guiding mechanism. Neither higher order HF modes nor SIF modes are allowed to propagate in that region, though the propagated mode is slightly altered by the doped core. It is possible to modify the propagated mode distribution in order to improve coupling efficiency from lasers or other fibers by carefully choosing the parameters of the DCHF within region I.

In the next regime (II), the SIF guiding mechanism is dominating and responsible for light propagation. The DCHF is still a single mode fiber, but most of the energy in the fundamental mode is contained within the doped core. In this case one may have the most efficient response for light amplified in the doped core or of the Bragg grating confined in the photo-sensitive core and still be able to slightly modify the guiding conditions by adapting the DCHF parameters.

In regime (III) the two next modes start to propagate. However, they are guided through the HF guiding mechanism and at the same time the fundamental mode is guided by the SIF guiding mechanism. This coexistence of both guiding methods brings forward very interesting mode intensity distributions (Fig. 4B, 4C). The fundamental mode is almost totally confined in the doped core, while most of the energy of the second order modes is placed outside of the higher refractive index doped core. Moreover, the higher order modes are highly birefringent: B~10^{-3} (Fig. 4A). If the coupling coefficient between the fundamental and higher order modes is low and if we assume that the fundamental mode is reflected by the Bragg grating written in the doped core then we may expect unusual light propagation outside of the doped core and the only propagating modes are highly birefringent.

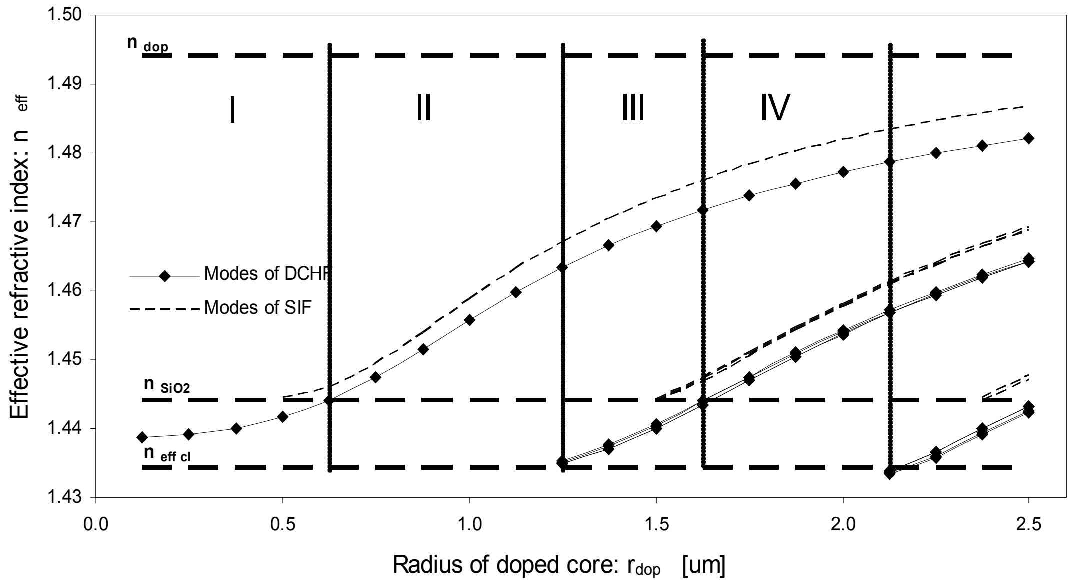


Figure 3. Effective refractive indices of guided modes vs. radius of doped core for a given doping level (n_{dop}=1.494) shown on graph with horizontal line, structure (Λ=5 μm; ρ = 1μm) and wavelength (λ =1.55 μm). Solid curves represent modes guided in DCHF and dashed curves stand for modes propagated without HF structure (modes of SIF). Two dashed horizontal lines represent respectively the refractive index of silica (n_{SiO2}) and the effective refractive index of the HF cladding. Dotted vertical lines are the borders between four (I-IV) different propagation regimes of guided modes.

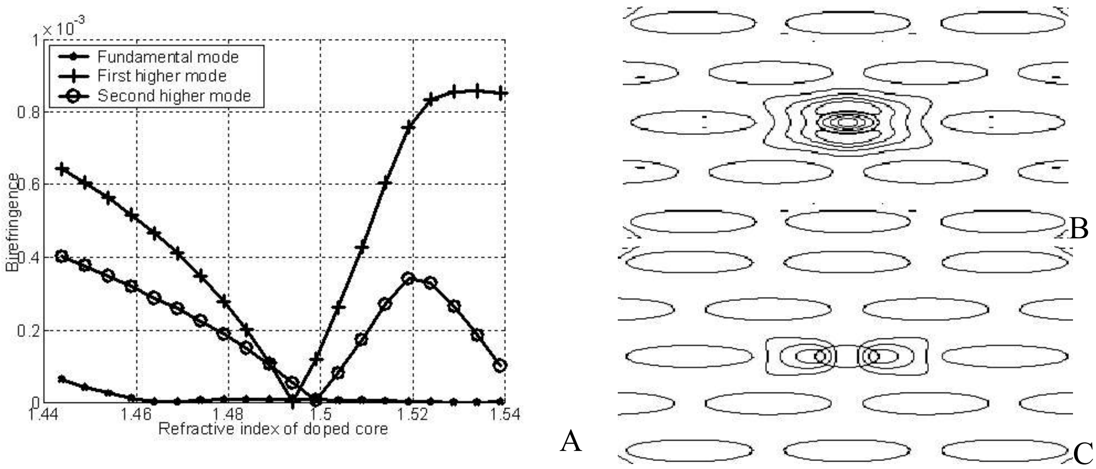


Figure 4. Birefringence in DCHF of fundamental, first and second higher order modes (A). Intensity distribution of first (B) and second (C) higher order modes from (A) and propagating in regime III as illustrated in Fig. 3.

The fourth (IV) guiding regime consists of the fundamental and second order modes propagating within the doped core by the SIF mechanism, so most of the energy is concentrated in the doped core.

Conclusions

Because of a lack in study of HF with doped regions we have made a first investigation of these types of fibers, which might play an important role both in telecom or sensing applications.
Indeed, a DCHF gives more opportunities for tailoring and designing the intensity distribution of the guided modes, which can be an asset of this type of HF with respect to the classical doped core step index fiber.
The extensive study of the mode distributions, effective refractive indices and the number of guided modes of the DCHF proved that single mode propagation is possible for a relatively large range of refractive indices of doped cores (propagating regimes I and II). At the same time the propagated mode responds stronger to the Bragg grating or to the active region amplifying the optical signal, whichever of the two functionalities are present.
Two main guiding mechanisms help to explain the propagation regimes of the DCHF and clearly support the numerical results.
Moreover our simulations indicate an unusual guided mode propagation (regime III) outside the higher refractive index region, which was reserved up to now for photonic band gap fibers only. Based on the latter phenomenon we could construct a highly birefringent fiber with also high sensitivities for multi-parameter (temperature and mechanical) sensing.

References

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