Dual-Core Elliptical Hollow Optical Fiber with Linearly Wavelength-Decreasing Birefringence

Minkyu Park(1), Luca Schenato(2), Luca Palmieri(2), Sejin Lee(1), Andrea Galtarossa(2), Kyunghwan Oh(1)

(1) Department of Physics, Yonsei University, 134 Shinchon-dong, Seoul, 120-749, Republic of Korea.
(2) Department of Information Engineering, University of Padova, Via Gradenigo, 6/B, Padova, 35131, Italy, ✉ luca.schenato@dei.unipd.it

Abstract *An elliptical hollow fiber, with a central air hole surrounded by a germanosilicate lance-shaped ring, is numerically and experimentally characterized. The fiber behaves like a dual core waveguide, whose birefringence linearly decreases with wavelength.*

Introduction

Over the last few years, hollow-core optical fibers (HOF) have been proposed as viable solutions in a wide range of applications, spreading from optical communication technology[1,2], to sensing[3] and spectroscopy[4]. Among the possible different solutions, this paper focuses on HOFs that guide light by conventional step-index difference between the ring core and surrounding material[2,5]. Actually, this configuration improves the compatibility with standard single-mode fibers (SMF) and, furthermore, allows to achieve high birefringence by making the ring core (and possibly the inner hole) asymmetrical.

In particular, the elliptical HOF (EHOF) described in this paper has been drawn from a side-ground preform, accordingly to the procedure already reported by Jung *et al.*[6]. As shown Fig. 1, the fiber has an elliptical air hole, surrounded by a lance-shaped germanosilicate ring with peaks aligned along the major axis of the hole. Numerical analyses, confirmed by experimental results, have shown that the fiber behaves like a dual-core waveguide, whose birefringence has the property of being linearly decreasing with wavelength.

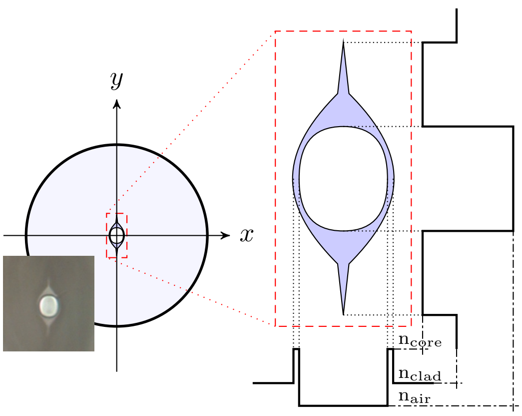

Fig. 1: Cross section of EHOF. In the inset: microscopic picture of the core taken by illuminating one end.

Mode analysis

Mode analysis of the EHOF was firstly carried out by numerical simulations with Finite Element Method. The dimensions of cross section used for simulation have been inferred by analyzing microscopic images of one end of the fiber while illuminating the other one with a light source (see the inset of Fig. 1). Major and minor axes of the elliptical hole are 9.24 μm and 8.14 μm, respectively, whereas the lance-shaped ring appears to $\sim 0.2\mu$m larger than the air-hole along x-axis and almost 3 times longer along y-axis. The refractive index difference between silica cladding and Ge-doped ring is about 1%.

Numerical simulations show that the four lowest order modes are x-polarized even, x-polarized odd, y-polarized even and y-polarized odd; their effective refractive indices are represented in Fig. 2 as a function of wavelength. Figure 3 shows the corresponding normalized power densities: as one can note, fields are mostly confined in the peaked lobes of the GeO_2 doped-ring. In the following these two lobes will be simply referred as "cores".

Note that the effective indeces of the even and the odd modes with the same polarization are practically overlapped, hence we conclude that

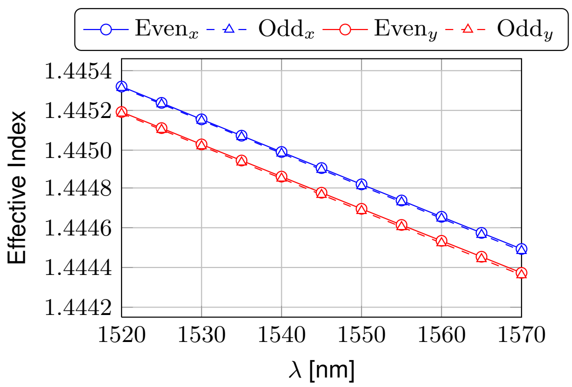

Fig. 2: Effective index vs. wavelength for the first four modes of EHOF provided by FEM simulations.

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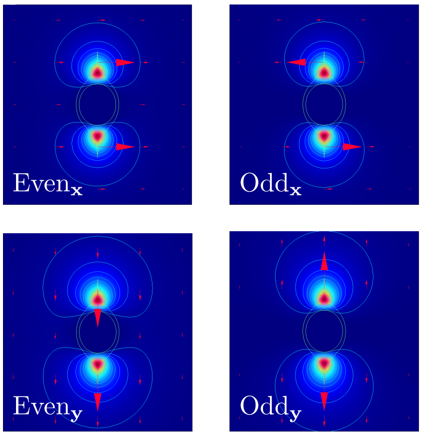

Fig. 3: Normalized power densities at 1550 nm.

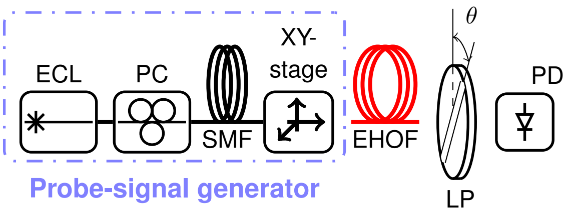

Fig. 4: Setup for experimental characterization of the polarization properties of the EHOF.

the two cores are practically not coupled and each core behaves like an independent waveguide. Moreover, the high asymmetry of the doped ring results in a strong difference between the effective indeces of orthogonal polarizations.

Experiments

The properties of the EHOF have been characterized by probing the fiber with a CW external cavity tunable laser (ECL, 1500-1600 nm), air-coupled to the EHOF by means of a high precision XY-stage (see Fig. 4). Upon varying the alignment, we were able to excite either each core individually or both cores simultaneously. Effectiveness of this procedure has been verified by observing the emerging field with an analog infrared camera (Fig. 5).

To prove that the two cores are not coupled, we set the alignment so to exicite only one core, and then the ECL wavelength was continously swept in the range 1500-1600 nm. Meanwhile, the spatial distribution of the output power was monitored with IR camera, showing that there was not transfer of power from one core to the other. This confirms that the two cores are practically independent waveguides.

Due to geometrical asymmetry of each core, we expect them to behave like highly birefringent waveguides. The characterization of polarization properties has been performed with the wavelength scanning method[7] and the actual setup is

Fig. 5: Emerging field by changing mutual alignment between launching patch cord and EHOF: (a) only core No.1 is excited; (b) both cores are excited simultaneously; (c) only core No.2 is excited.

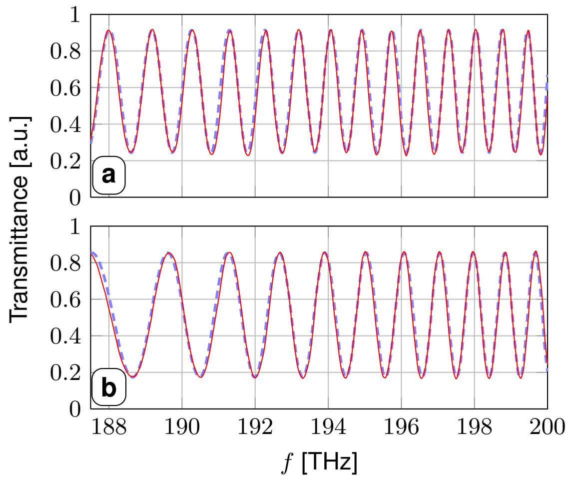

Fig. 6: Solid red curves: normalized transmittance $T(f)$ of the first core (a) and second core (b) for a given input SOP. Dashed blue curves: fitting function $\hat{T}(f)$ of transmittance curve.

depicted in Fig. 4. In the probe-signal generation, a polarization controller (PC) allows for the control of the input state of polarization (SOP) of the signal launched into the EHOF and the XY-stage permits to select the core to be excited. The emerging signal was detected by a photodiode (PD) after being passed through a linear polarizer (LP), which could be oriented at an arbitrary angle.

More in detail, the transmitted power was measured for two orthogonal orientations of the output linear polarizer, so to compensate for possible polarization independent losses. Actually, let A_0 and $A_{\pi/2}$ be the corresponding voltage output of the PD, then the normalized transmittance of the EHOF as a function of the frequency $f = c_0/\lambda$ is $T(f) = \left[1 + (A_0 - A_{\pi/2})/(A_0 + A_{\pi/2})\right]/2$. This transmittance was measured for 5 different input SOP, to increase the accuracy.

As an example, solid curves of Fig. 6 represent the normalized transmittances of the first (sub-plot (a)) and second (sub-plot (b)) core, as a function of the frequency, for a specific input SOP. The chirped oscillatory behavior is due to the beating of the two polarization modes that propagate in each core. Note that the beat frequencies of the two cores are patently different.

In order to extrapolate birefringence information, the normalized transmitted power $T(f)$ has

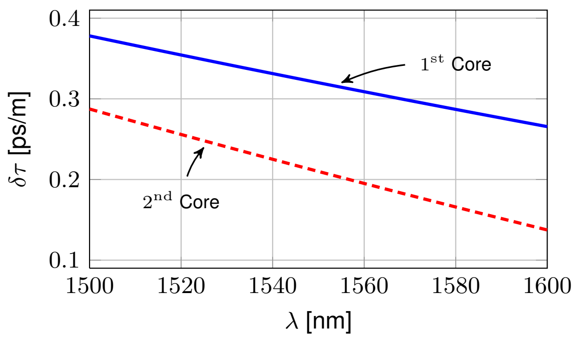

Fig. 7: DGD per unit length, $\delta\tau$, of first (solid blue curve) and second (dashed red curve) core.

been fitted with the function

$$\hat{T}(f) = \frac{1 + a_0 \sin\left[2\pi L\left(\delta\tau_0 + \delta\tau_1 \Delta f\right)\Delta f + \phi_0\right]}{2},$$

where $\Delta f = f - f_0$, $f_0 = 193.55$ THz ($\lambda_0 = 1550$ nm), $L = 2.97$ m is the EHOF length. Note that the term $\delta\tau(f) \triangleq \delta\tau_0 + \delta\tau_1\Delta f$ represents the PMD coefficient (differential group delay, DGD, per unit length) experienced by the field as a function of frequency: accordingly, $\delta\tau_0$ is the PMD coefficient at 193.55 THz (1550 nm) and $\delta\tau_1$ is the PMD coefficient slope, i.e. $\delta\tau_1 = \mathrm{d}\delta\tau/\mathrm{d}f$.

Parameters $a_0, \delta\tau_0, \delta\tau_1$ and ϕ_0 have been determined by least squares method: they are listed in Tab. 1 and the corresponding fitting curves are represented in Fig. 6, with dashed curves. The resulting PMD coefficient is shown in Fig. 7 as a function of wavelength, with the solid and the dashed curves corresponding to the first and second core, respectively.

As one can see from Tab. 1 and Fig. 7, the differential group delay per length unit of the two cores do not coincide: the gap between the two curves is ~ 0.1 ps/m at 1500 nm and broadens for wavelength increasing. This can be explained by a slight asymmetry with respect to the x axis. In spite of this, cores behave similarly with respect to wavelength dependence: indeed, birefringence linearly decreases with wavelength quite rapidly. In particular, the DGD per unit length is almost halved in 100 nm. A similar unusual behavior was previously observed for photonic band gap fiber with asymmetric hollow core[8], which had, however, a far more complex design.

In conclusion, an elliptical hollow fiber with lance-shaped core ring has been investigated, both numerically and experimentally. Experimental measurements as well as numerical simulations show that the fiber behaves like a dual-core waveguide and, more interestingly, the two cores exhibit a fairly high birefringence, which linearly decreases with wavelength.

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Tab. 1: Parameters of the two cores according to experimental measurements.

Core	No.1	No.2
$\delta\tau_0$ [ps/m]	0.32	0.21
$\delta\tau_1$ [ps/m/THz]	0.009	0.012

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