



HAL
open science

Phase shift induced degradation of polarization caused by bends in inhibited-coupling guiding hollow-core fibers

Christian Röhrer, Jonas Osorio, Frieder Beirow, Martin Maurel, Benoît Debord, Thomas Graf, Frédéric Gérôme, Fetah Benabid, Marwan Abdou Ahmed

► To cite this version:

Christian Röhrer, Jonas Osorio, Frieder Beirow, Martin Maurel, Benoît Debord, et al.. Phase shift induced degradation of polarization caused by bends in inhibited-coupling guiding hollow-core fibers. IEEE Photonics Technology Letters, 2019, 31 (16), pp.1362-1365. 10.1109/LPT.2019.2927046 . hal-02327997

HAL Id: hal-02327997

<https://hal.science/hal-02327997>

Submitted on 7 Jul 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Phase Shift Induced Degradation of Polarization Caused by Bends in Inhibited-Coupling Guiding Hollow-Core Fibers

Christian Röhrer¹, Jonas H. Osório², Frieder Beirrow, Martin Maurel, Benoît Debord, Thomas Graf, Frédéric Gérôme, Fetah Benabid, and Marwan Abdou Ahmed

Abstract—We report on a comprehensive analysis of the polarization-maintaining (PM) behavior of two different kinds of inhibited-coupling (IC) guiding hollow-core fibers and the influence of fiber bends. A phase shift induced degradation of the incident linear polarization state was observed due to a mismatch of the propagation constants of the orthogonally polarized LP₀₁-modes of the fiber. This effect was predicted theoretically and is corroborated with numerical simulations and experimental results. It is shown that the phase shift is enhanced by a reduction of the bending radius of the fiber but can be circumvented by orienting the polarization of the injected beam either parallel or perpendicular to the plane of bending.

Index Terms—Fiber properties, hollow-core fibers, polarization-maintaining fibers, photonic crystal fibers.

I. INTRODUCTION

THE availability of ultrafast lasers with high peak powers and high pulse energies is beneficial for a wide range of material processing applications, like the drilling of high-aspect ratio holes, high-quality and high-throughput cutting, and surface structuring [1]. It is also known that for most of these processes the polarization can be a crucial parameter [2]. Since ultrafast lasers emit a polarized laser beam, it is highly desirable to keep this polarization state. To allow for a flexible beam delivery of pulses with high peak powers from the laser-source to the targeted workpiece, inhibited-coupling (IC) guiding hollow-core photonic crystal

fibers (HC-PCFs) [3]–[5] have been proven to be the most appropriate choice.

In solid-core fibers, the polarization-maintaining (PM) property is accomplished by the exploitation of birefringence. This can be introduced by intentionally implementing an asymmetrical mechanical stress distribution in the core of the fiber [6] or by breaking the core's symmetry [7]. Breaking the symmetry of the fiber to enhance the birefringence and maintain the polarization has also been proposed for IC HC-PCFs. This can be implemented by using an elliptical core [8], by modifying the thickness of the glass along one fiber axis [9], [10] or by implementing nested resonant tubes [11], but such solutions come at the cost of a high transmission loss.

However, IC HC-PCFs can exhibit a strong polarization-maintaining behavior without specially designing these fibers to be PM [12]. In fact, due to the inhibited-coupling mechanism both orthogonally polarized LP₀₁-modes are isolated from external perturbations and can therefore propagate without interaction. This was demonstrated for the two most commonly used types of IC HC-PCFs, where polarization extinction ratio (PER) values as high as 26 dB and 15.5 dB could be demonstrated for a 3 m long hypocycloid-shaped 7-cell Kagome lattice fiber [13] and for a single-ring tubular lattice fiber with a length of 16 m [4], respectively. For the latter type of fiber, a detailed analysis was recently published by Jayakumar *et al.* [14], where it was stated that the symmetry of the core geometry has a direct impact on the polarization. However, in the above mentioned publications [4], [12], [13], no such dependence was observed.

Since the studies so far on birefringence in IC HC-PCFs were purely based on numerical simulations [8]–[11] or were limited to comparatively short and straight fibers of about 12 cm [14] a more detailed analysis of the polarization-maintaining behavior of bent hollow-core fibers is required. This is particularly important for IC HC-PCFs due to their suitability for the delivery of pulses with high peak powers or high-brightness cw laser beams [5]. In this letter we therefore present a comprehensive theoretical and experimental investigation on two types of IC HC-PCFs regarding their polarization-maintaining behavior and corroborate the theoretically predicted effects and mechanisms with numerical simulations and experimental measurements. It is shown that bending the fibers induces a mismatch in the propagation constants of the orthogonally polarized LP₀₁-modes.

Manuscript received May 31, 2019; revised June 25, 2019; accepted July 1, 2019. Date of publication July 5, 2019; date of current version July 31, 2019. This work was supported in part by the Horizon 2020 Framework Programme (H2020) under Grant HIPERDIAS 687880, in part by the Deutsche Forschungsgemeinschaft (DFG) under Grant GSC 262/2, and in part by the Agence Nationale de la Recherche (ANR) under Grants Σ _LIM Labex Chaire, DGA Astrid-Maturation Plasma-PMC. (Corresponding author: Christian Röhrer.)

C. Röhrer, F. Beirrow, T. Graf, and M. Abdou Ahmed are with the Institut für Strahlwerkzeuge (IFSW), University of Stuttgart, 70569 Stuttgart, Germany (e-mail: christian.rohrer@ifsw.uni-stuttgart.de; frieder.beirrow@ifsw.uni-stuttgart.de; thomas.graf@ifsw.uni-stuttgart.de; marwan.abdou-ahmed@ifsw.uni-stuttgart.de).

J. H. Osório is with the GPPMM Group, Xlim Research Institute, University of Limoges, 87032 Limoges, France (e-mail: jonas-henrique.osorio@xlim.fr).

M. Maurel, B. Debord, F. Gérôme, and F. Benabid are with the GPPMM Group, Xlim Research Institute, University of Limoges, 87032 Limoges, France, and also with GLOphotonics S.A.S, 87060 Limoges, France (e-mail: martin.maurel@xlim.fr; benoit.debord@xlim.fr; frederic.gerome@xlim.fr; f.benabid@xlim.fr).

Color versions of one or more of the figures in this letter are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/LPT.2019.2927046

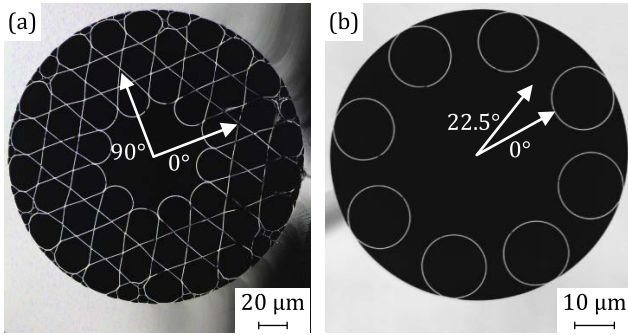


Fig. 1. Microscope images of the analyzed fibers. (a) K-7C. (b) T-8.

This leads to a phase shift which can degrade the incident linear polarization. In our investigations a hypocycloid-shaped 7-cell fiber with a Kagome lattice, referred to as K-7C (see Fig. 1 (a)), and a fiber consisting of a single-ring tubular lattice, referred to as T-8 (see Fig. 1 (b)), were analyzed. Both fibers are similar to already published fiber designs [3], [4] and are commercially available [15]. The K-7C fiber operates in the second transmission band with a nominal loss of < 50 dB/km for wavelengths ranging from 900 nm to 1100 nm [3]. The T-8 fiber operates in the first transmission band and therefore offers a broad spectral bandwidth with a nominal loss < 21 dB/km in the wavelength range from 600 nm to 1200 nm [4].

Since the background of this work is the flexible beam delivery of high-brightness laser beams, the investigations concentrate on the polarization state of the fundamental mode and neglect any higher-order modes, which may have an influence on the polarization state as it was shown in a previous publication [4]. While there is no preferred axis of symmetry in an ideal waveguide with a circular cross-section [16], in bent fibers the electromagnetic modes are polarized either parallel or perpendicular to the bending plane. An incident linearly polarized laser beam therefore excites a mixture of the two orthogonally polarized LP_{01} -modes, unless the polarization of the incident beam is either parallel or perpendicular to the bending plane. In this case, only one of the two orthogonally polarized LP_{01} -modes is excited. If both modes are excited, a difference between their propagation constants $\Delta n_{\text{eff}} \neq 0$ results in a change of the polarization of the transmitted light.

II. NUMERICAL SIMULATIONS

In order to calculate the value of Δn_{eff} , numerical simulations based on the finite element method (FEM) were performed by using the commercially available software COMSOL Multiphysics. For our simulations the whole cross section of the fiber was considered, which is surrounded by a perfectly matched layer (PML) [17] with a thickness of $10 \mu\text{m}$. In order to account for fiber bends with different bending directions the improved bend-loss formula [18] was implemented in our simulations. The fiber geometries which were used in the simulations were extracted from the microscope images shown in Fig. 1. The fiber K-7C has a core diameter of $61 \mu\text{m}$ and a strut thickness of 700 nm , whereas the T-8 fiber has a core diameter of $42 \mu\text{m}$ and a strut thickness of 225 nm . For all numerical simulations the wavelength λ was

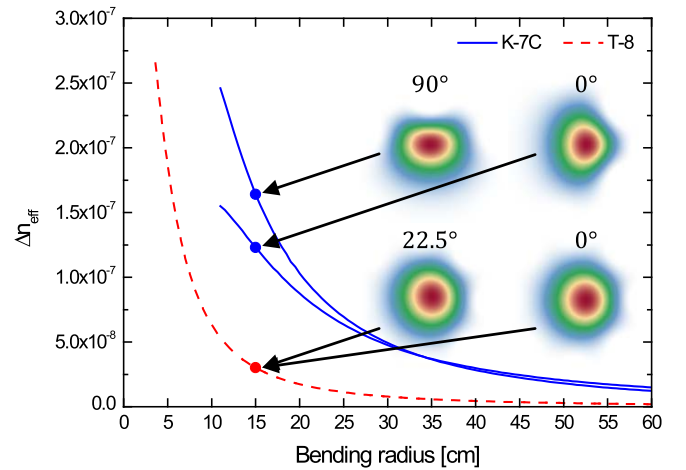


Fig. 2. Calculated Δn_{eff} between the orthogonally polarized LP_{01} -modes as a function of the bending radius for different bending directions (see Fig. 1) at a wavelength of 1050 nm. Insets: Intensity distributions of the LP_{01} -modes for a bending radius of 15 cm for the K-7C and the T-8 fiber at different bending directions.

set to 1050 nm. Simulations were performed for different bending radii of the fibers and for different bending directions, since the non-rotational symmetric core contour can influence the modal behavior. Two different bending directions were simulated for each fiber type, as marked by the white arrows in Fig. 1. These are the two extreme cases, which correspond to bending against the outer cup (0°) and inner cup (90°) for the K-7C fiber, and bending against the lattice tube (0°) and the gap between two tubes (22.5°) for the T-8 fiber.

Fig. 2 shows the influence of the bending radius on the calculated Δn_{eff} between the two orthogonally polarized LP_{01} -modes. It is seen that Δn_{eff} increases with diminishing bending radius and is larger for the K-7C fiber than for the T-8 fiber. Even though both fibers have different core diameters and therefore different modal properties, we attribute the observed behavior to their different cladding geometry, including the shape of the core's contour, the strut thickness, and to the fact that the operating wavelength lies within different transmission bands. This can also be confirmed by additional simulations, which are not shown here, which highlight that the fractional power of the fundamental mode in the surrounding silica is higher in the K-7C fiber than in the T-8 fiber. Hence the overlap and therefore the interaction with the cladding region is higher, which lifts the degeneracy and enhances the induced birefringence.

Fig. 2 also shows that the birefringence induced in the T-8 fiber is independent of the bending direction (both lines lay on top of each other). In contrast, a large influence of the bending direction on Δn_{eff} is observed for the K-7C fiber, especially at small bending radii. This is due to a strong mismatch of the propagation properties depending on the bending direction, which also becomes apparent from the shape of the modes (see insets Fig. 2 (top)). In contrast to the K-7C fiber, the LP_{01} -mode of the T-8 fiber is much more confined for all bending directions (see insets Fig. 2 (bottom)).

The bending direction with respect to the fiber structure is difficult to determine and control in the experimental investigations without excessive efforts. For the K-7C fiber

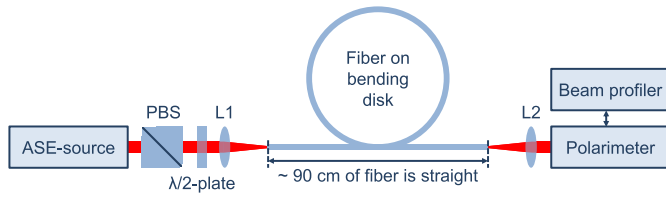


Fig. 3. Experimental setup used for all experimental investigations.

the average value of Δn_{eff} , obtained for the bending directions of 0° and 90° , is therefore used in the following to compare the simulation to the experimental results.

III. EXPERIMENTAL RESULTS

Fig. 3 shows the experimental setup. The diffraction-limited output beam of a fiber-coupled amplified spontaneous emission (ASE) light source, with a wavelength range of 1025 nm to 1075 nm, was polarized by means of a polarizing beam-splitter (PBS). A $\lambda/2$ -plate was used to control the orientation of the polarization of the linearly polarized beam before it was coupled into the tested fiber by the lens L1. The focal length of L1 was optimized beforehand for both fiber types in order to achieve mode-matching between the incident beam and the fundamental fiber mode to avoid excitation of higher-order modes at the fiber input. Most of the fiber was mounted on a bending disk to apply a defined bending radius, whereas the rest of the fiber with a length of approximately 90 cm was kept straight. The beam leaving the fiber at the rear end was collimated by the lens L2 and was analyzed in terms of polarization and beam quality with a commercially available polarization measurement device and a beam profiler, respectively. Using the Stokes formalism [19] to describe the polarization state, the used polarimeter retrieves all Stokes parameters, which yield to the degree of linear polarization (DOLP) [20] and ellipticity angle [19].

As a reference, a 90 cm long piece of fiber which was kept as straight as possible without applying stress to the fiber was tested in a first experiment. The orientation of the linear polarization of the incident beam was rotated stepwise from 0° (horizontal direction) to 90° (vertical direction) and further to 180° (horizontal direction). The overall behavior of both fibers is similar and the DOLP was close to 100 % for all orientations of the incident polarization. The DOLP was measured to be $99.4\% \pm 0.3\%$ and $99.5\% \pm 0.4\%$ for the K-7C and the T-8 fiber, respectively. Hence the linear polarization is maintained if the fiber is kept straight. This can also be verified with numerical simulations. For a straight fiber Δn_{eff} was calculated to be $1.79 \cdot 10^{-9}$ and $1.62 \cdot 10^{-11}$ for the K-7C and the T-8 fiber, respectively. By using the reciprocal of the beat length, which is defined as $L_B = \lambda / \Delta n_{\text{eff}}$ [16], one can calculate the phase shift $\delta = 2\pi \cdot \Delta n_{\text{eff}} / \lambda$ to be $0.61^\circ/\text{m}$ and $0.006^\circ/\text{m}$ for the K-7C and the T-8 fiber, respectively. Consequently, the influence of the straight section with a length of approximately 90 cm on the polarization is negligible in all the experiments presented here. Three different fiber lengths and four different bending radii were analyzed as listed in Table I.

TABLE I
DESIGN OF EXPERIMENTS FOR BOTH FIBERS WITH DIFFERENT FIBER LENGTHS L AND BENDING RADII r_{bend}

	$L = 2.25$ m	$L = 4.75$ m	$L = 7.25$ m
$r_{\text{bend}} = 50$ cm			2 windings
$r_{\text{bend}} = 20$ cm	1 winding	3 windings	5 windings
$r_{\text{bend}} = 10$ cm	2 windings	6 windings	10 windings
$r_{\text{bend}} = 5$ cm	4 windings	12 windings	20 windings

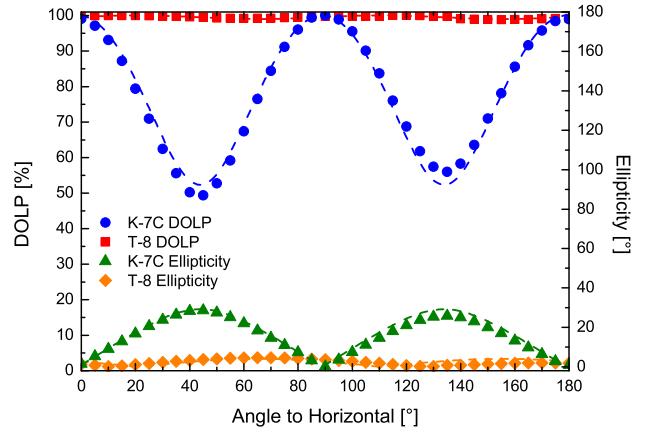


Fig. 4. Measured DOLP and ellipticity as function of the orientation of the polarization of the incident beam. The tested fibers were bent with a radius of 20 cm and had a length of 2.25 m. Dashed lines show the results of the fit using the Müller calculus.

Fig. 4 shows the experimental results obtained for the two fiber types with a length of 2.25 m each and a bending radius of 20 cm. For the T-8 fiber the DOLP is close to 100 % and is almost unaffected by a rotation of the polarization of the incident beam, which is very similar to the behavior of the straight fiber. In contrast to this, the polarization of the transmitted beam was found to strongly depend on the orientation of the polarization of the beam launched into the K-7C fiber. The DOLP of the transmitted beam is close to 100 % only when the polarization of the incident beam is either parallel (90°) or perpendicular (0° and 180°) to the plane of bending. At the same time the ellipticity is 0° . When the polarization of the incident beam is oriented at $\pm 45^\circ$ to the bending direction, the DOLP of the transmitted beam degrades strongly. Nevertheless, the measured beam quality of $M^2 = 1.1 - 1.2$ of the transmitted beams was almost constant and independent of the orientation of the polarization of the launched beam for both fiber types. Bent-induced mode coupling to higher-order modes can therefore be neglected.

To explain the observed behavior we use the Müller calculus [19]. A change of the polarization induced by any optical element can be expressed by applying a 4×4 transfer matrix M – known as the Müller matrix – to the Stokes vector \vec{S} of the incident radiation. The Stokes vector of the transmitted beam is given by $\vec{S}' = M \cdot \vec{S}$. The Müller matrix used to describe the phase shift induced by the Δn_{eff} in a fiber as considered here is the one of a general linear retarder, as given in [20]. The Müller calculus was used to fit the calculated DOLP values to the measured data by means of the least squares error using the phase shift δ as fit parameter (see dashed lines in Fig. 4). As can be seen the results

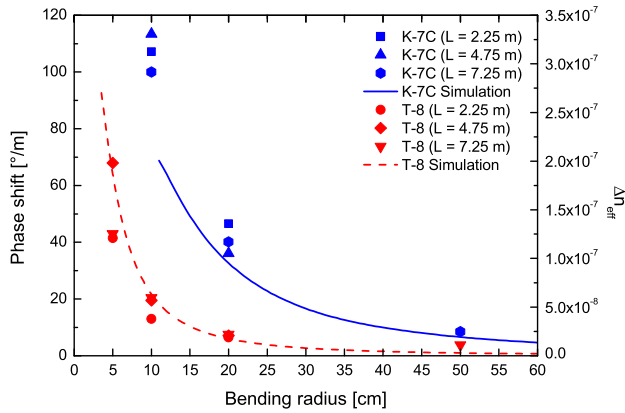


Fig. 5. Comparison between the experimental results for the bend-induced phase shift per length of the bent section and the numerical simulations (see Fig. 2) as function of the bending radius.

are in good agreement with the experiments, resulting in a phase shift of 58.5° and 8.1° for the K-7C and the T-8 fiber, respectively. Hence, the measured phase shift of the K-7C fiber is about 7 times stronger than the one of the T-8 fiber, which was already indicated by the numerical simulations (see Fig. 2), where Δn_{eff} between both orthogonally polarized LP₀₁-modes in the K-7C fiber is about 5.5 times larger than the one of the T-8 fiber.

To compare the experimental data to the calculation for all experimental combinations listed in Table I, the experimental data was fit using the Müller calculus and the resulting phase shift was normalized by the length of the bent fiber section. Fig. 5 shows the results of this comparison. The results obtained for the K-7C fiber at a bending radius of 5 cm are not included as it was noticed that in this case the transmitted beam was strongly distorted and did not correspond to the fundamental mode anymore. Here, the measured beam quality factor M^2 increases to up to 3, in contrast to 1.1 – 1.2 for all other results shown in Fig. 5. The results show that within the accuracy of the measurement the induced phase shift per unit length is constant at a fixed bending radius. This is in accordance with the theory showing that a difference of the propagation constants of both orthogonally polarized LP₀₁-modes leads to a phase shift proportional to the fiber length. The experimental data exhibits an increase of the phase shift with decreasing bending radius, which fits well to the simulation and it can be concluded that the phase shift for the K-7C fiber is 5 times larger than the one of the T-8 fiber.

IV. CONCLUSION

In conclusion we have discussed the influence of fiber bends on the polarization-maintaining behavior of two different kinds of IC HC-PCFs. A bending-induced change of the difference Δn_{eff} of the propagation constants of the two orthogonally polarized LP₀₁-modes leads to a phase shift between both modes and this can cause a degradation of the linear polarization of the transmitted beam. To circumvent

this, bending radii of some tens of centimeters have to be applied or the polarization direction should be orientated either parallel or perpendicular to the plane of the bending. The K-7C fiber exhibits a stronger mismatch Δn_{eff} and as a result a stronger phase shift compared to the fiber T-8. The results found call for further studies on the polarization properties of IC-guiding fibers, which will allow for the development of improved fiber designs in terms of polarization-maintaining behavior.

REFERENCES

- [1] K. Sugioka and Y. Cheng, "Ultrafast lasers—Reliable tools for advanced materials processing," *Light Sci. Appl.*, vol. 3, Apr. 2014, Art. no. e149.
- [2] H. Hügel and T. Graf, *Laser in der Fertigung: Grundlagen der Strahlquellen, Systeme, Fertigungsverfahren*. Berlin, Germany: Springer, 2014.
- [3] B. Debord *et al.*, "Hypocycloid-shaped hollow-core photonic crystal fiber Part I: Arc curvature effect on confinement loss," *Opt. Express*, vol. 21, no. 23, pp. 28597–28608, 2013.
- [4] B. Debord *et al.*, "Ultralow transmission loss in inhibited-coupling guiding hollow fibers," *Optica*, vol. 4, no. 2, pp. 209–217, 2017.
- [5] B. Debord, F. Amrani, L. Vincetti, F. Gérôme, and F. Benabid, "Hollow-core fiber technology: The rising of 'Gas Photonics,'" *Fibers*, vol. 7, no. 16, pp. 1–58, Feb. 2019.
- [6] T. Hosaka, K. Okamoto, T. Miya, Y. Sasaki, and T. Edauro, "Low-loss single polarisation fibres with asymmetrical strain birefringence," *Electron. Lett.*, vol. 17, no. 15, pp. 530–531, Jul. 1981.
- [7] R. B. Dyott, J. R. Cozens, and D. G. Morris, "Preservation of polarisation in optical-fibre waveguides with elliptical cores," *Electron. Lett.*, vol. 15, no. 13, pp. 380–382, Jun. 1979.
- [8] L. Vincetti and V. Setti, "Elliptical hollow core tube lattice fibers for terahertz applications," *Opt. Fiber Technol.*, vol. 19, no. 1, pp. 31–34, Jan. 2013.
- [9] W. Ding and Y. Y. Wang, "Hybrid transmission bands and large birefringence in hollow-core anti-resonant fibers," *Opt. Express*, vol. 23, no. 16, pp. 21165–21174, 2015.
- [10] S. A. Mousavi, S. R. Sandoghchi, D. J. Richardson, and F. Poletti, "Broadband high birefringence and polarizing hollow core antiresonant fibers," *Opt. Express*, vol. 24, no. 20, pp. 22943–22958, 2016.
- [11] C. Wei, C. R. Menyuk, and J. Hu, "Polarization-filtering and polarization-maintaining low-loss negative curvature fibers," *Opt. Express*, vol. 26, no. 8, pp. 9528–9540, 2018.
- [12] A. Amsanpally, "Linear properties of inhibited coupling hollow-core photonic crystal fibers," Ph.D. dissertation, XLIM Res. Inst., Univ. Limoges, Limoges, France, 2017.
- [13] M. Maurel *et al.*, "Optimized inhibited-coupling Kagome fibers at Yb-Nd:Yag (8.5 dB/km) and Ti:Sa (30 dB/km) ranges," *Opt. Lett.*, vol. 43, no. 7, pp. 1598–1601, 2018.
- [14] N. Jayakumar *et al.*, "Polarization evolution in single-ring antiresonant hollow-core fibers," *Appl. Opt.*, vol. 57, no. 29, pp. 8529–8535, 2018.
- [15] *GLOphotonics*. Accessed: Mar. 6, 2019. [Online]. Available: <http://www.glophotonics.fr/>
- [16] A. W. Snyder and J. D. Love, *Optical Waveguide Theory*. Boston, MA, USA: Springer, 1983.
- [17] J.-P. Berenger, "A perfectly matched layer for the absorption of electromagnetic waves," *J. Comput. Phys.*, vol. 114, no. 2, pp. 185–200, Oct. 1994.
- [18] R. T. Schermer and J. H. Cole, "Improved bend loss formula verified for optical fiber by simulation and experiment," *IEEE J. Quantum Electron.*, vol. 43, no. 10, pp. 899–909, Oct. 2007.
- [19] E. Collett, "Field guide to polarization," in *SPIE Field Guides*, vol. FG05, J. E. Greivenkamp, Ed. Bellingham, WA, USA: SPIE, 2005, p. 1134.
- [20] R. A. Chipman, "Polarimetry," in *Handbook of Optics, Vol. 2, Devices, Measurements, and Properties*, M. Bass, E. W. van Stryland, D. R. Williams, and W. L. Wolfe, Eds. New York, NY, USA: McGraw-Hill, 1994, pp. 22.1–22.37.