



HAL
open science

Next-Generation Tunable All-Fiber Mach-Zehnder Interferometers in Hollow Core Fibers

Ricardo E da Silva, Jonas H Osório, Frédéric Gérôme, Fetah Benabid, Cristiano M B Cordeiro

► **To cite this version:**

Ricardo E da Silva, Jonas H Osório, Frédéric Gérôme, Fetah Benabid, Cristiano M B Cordeiro. Next-Generation Tunable All-Fiber Mach-Zehnder Interferometers in Hollow Core Fibers. SBFoton International Optics and Photonics Conference, Nov 2024, Salvador, Brazil. pp.TS-WED-C1-4. hal-04828368

HAL Id: hal-04828368

<https://hal.science/hal-04828368v1>

Submitted on 10 Dec 2024

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.

Next-Generation Tunable All-Fiber Mach-Zehnder Interferometers in Hollow Core Fibers

Ricardo E. da Silva
Institute of Physics Gleb Wataghin
University of Campinas
Campinas, Brazil
resilva@unicamp.br

Fetah Benabid
XLIM Institute, CNRS UMR 7252
University of Limoges
Limoges, France
f.benabid@xlim.fr

Jonas H. Osório
Department of Physics
Federal University of Lavras
Lavras, Brazil
jonas.osorio@ufla.br

Cristiano M. B. Cordeiro
Institute of Physics Gleb Wataghin
University of Campinas
Campinas, Brazil
cmbe@ifi.unicamp.br

Frédéric Gérôme
XLIM Institute, CNRS UMR 7252
University of Limoges
Limoges, France
frederic.gerome@xlim.fr

Abstract— We demonstrate a new acousto-optic Mach-Zehnder interferometer (MZ) based on a hollow core fiber (HCF). The fabricated acousto-optic device excites two MZs in a 7.5 cm long HCF. In the first MZ, the HCF is attached in a centrally positioned acoustic driver, exciting two acoustically induced long period gratings. The second MZ induces two strong curvatures at the edges of the attached HCF-driver length. The MZs tune the free spectral range of the modulated multiwavelength spectrum by changing the driver’s frequency in steps of 1 Hz while providing compactness, efficiency, and high sensitivity, suitable for dynamic filters and fiber sensors.

Keywords—acousto-optic devices, long period gratings, Mach-Zehnder interferometers.

I. INTRODUCTION

Acousto-optic devices based on optical fibers enable highly sensitive dynamic sensors providing good resistance for the characterization of chemical, food, and biomedical applications [1], [2]. On the other hand, all-fiber Mach-Zehnder interferometers (MZs) are attractive for sensing strain, humidity, refractive index, temperature, fuel, and gases [3], [4], [5], [6]. In MZs, the optical beam is split to travel distinct optical paths which are further recombined interfering at the fiber output. The interference fringes have the free spectral range (FSR) tuned by changing the beams' relative phase.

Optical fibers provide notable features to enable multiple optical path lengths by means of distinct guided modes. These path lengths can be altered in MZs by employing concatenated fibers with different cross sections. The input beams can be coupled or split by fabricating two-point perturbations changing the refractive index or structure of the fiber cross section, e.g., by employing tapering [7], [8] or two symmetric bends nearly separated along the fiber [6]. Besides, MZs including two inscribed or pressure-induced long period gratings (LPGs) have been reported in sensing applications [3], [5], [9]. MZs based on LPGs provide tunable notch wavelength and magnitude by changing respectively the grating period and modulated refractive index amplitude.

Alternatively, acoustically modulated MZs provide additional electrical tuning of LPG properties and its

transmission spectrum. The acoustically induced LPGs are caused by bend-induced geometric deformation of the fiber changing the optical path length of the guided modes. The dynamic LPGs couple power between the fundamental and higher order modes at a resonant wavelength and depth defined respectively by the acoustic frequency and amplitude [10], [11]. The acousto-optic devices generally use tapered and etched fibers to reduce the fiber diameter and increase the modulation efficiency. Nevertheless, FSR tuning is usually limited to small variations induced by applied temperature or strain. Thus, relevant FSR tuning and generation of multiple fringes usually require replacing long fibers in between the two LPGs, resulting in the fabrication of additional MZs with distinct dimensions, which might increase the overall device size, consumed energy, switching time, and insertion losses [12].

We have recently numerically and experimentally demonstrated acoustically induced LPGs in tubular and hybrid-lattice HCFs [10], [11]. Here, we demonstrate a new all-fiber in-line dual MZ inside a hybrid kagome-tubular HCF. The fabricated acousto-optic modulator employs a centered-positioned acoustic driver, providing unique features to generate multiple resonant wavelengths by tuning the electrical frequency in 1 Hz steps. The results are analyzed and discussed for further sensing applications.

II. EXPERIMENTAL SETUP AND METHODS

Fig. 1(a) illustrates the experimental setup with the acousto-optic modulator (AOM), composed of an HCF segment of length L , a piezoelectric transducer (PZT), and a silica acoustic horn. The AOM is fabricated by employing a silica-made hybrid lattice HCF with a cross section formed by 800 nm thick Kagomé struts and 20 μm diameter tubes (1.25 μm thickness), as seen in Fig. 1(b). The HCF has a 34 μm diameter air core and is 240 μm in outer diameter, as described in detail in [13]. The PZT is 2 mm in thickness and 25 mm in diameter. The horn is 1.8 cm long and has the diameter tapered from 4.8 to 0.65 mm. The AOM connections are similar as in [10]. The HCF ends are fixed resulting in a total device length of $L = 7.5$ cm.

This work was supported by the grants 2022/10584-9, 2024/02995-4, São Paulo Research Foundation (FAPESP), 309989/2021-3, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), RED-00046-23 and APQ-00197-24, Minas Gerais Research Foundation (FAPEMIG). The authors thank F. Amrani and F. Delahaye for their contribution to fiber fabrication.

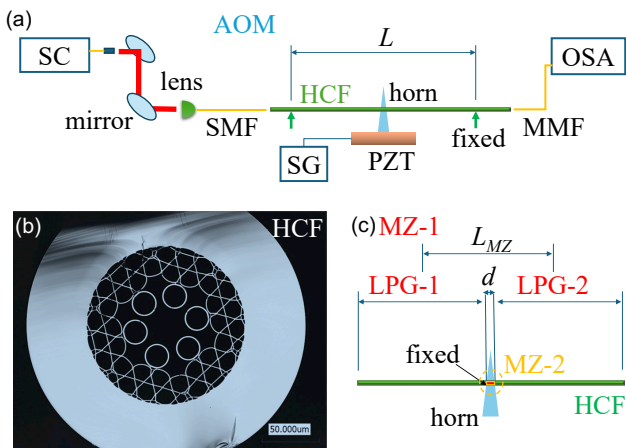


Fig. 1. (a) Experimental setup and acousto-optic modulator (AOM) using a piezoelectric transducer (PZT), an acoustic horn and an HCF segment of length L . (b) Hybrid-lattice hollow core fiber (HCF) and (c) details of the Mach-Zehnder interferometers (MZs).

The HCF input is butt-coupled to a standard single-mode optical fiber (SMF) connected to a supercontinuum laser source (SC) using a lens. The HCF output is butt-coupled to a multimode optical fiber (MMF) connected to an optical spectrum analyzer (OSA). A signal generator (SG) is used to excite the PZT with a maximum 10 V voltage sinusoidal electrical signal.

Fig. 1(c) illustrates the two MZs in the AOM, indicating the connection of the horn and HCF. MZ-1 is assembled by placing the acoustic driver centered along the HCF and attaching the fiber with the horn along the length d , splitting the fiber into two equivalent lengths (~ 3.7 cm). MZ-1 has a cavity length of $L_{MZ} \sim 3.9$ cm. The acoustically induced LPG-1 and LPG-2 couple power between the fundamental mode to higher order modes supported by the HCF air core [11, 13]. Fig. 1(c) indicates MZ-2 located in the separation region of $d \sim 1.6$ mm between the LPGs. The pressure caused by the LPGs in the fixed fiber d edges induces two strong curvatures coupling higher order modes in addition to those in MZ-1. Thus, MZ-2 curvatures work as a two-point coupler increasing the modes effective index n_{eff} . The FSR is tuned as [14],

$$\text{FSR} \approx \frac{\lambda^2}{\Delta n_{\text{eff}} L_{MZ}}. \quad (1)$$

where, Δn_{eff} is the modes effective refractive index difference, λ is the optical wavelength and, L_{MZ} is the center-to-center LPGs separation.

The AOM modulates a notch at $\lambda_C = 1176$ nm in the HCF transmission spectrum at $f = 264.064$ kHz (although is not shown, other modulated notches could also be tuned from $\lambda = 800$ to 1200 nm). The fringes' FSR is tuned by adjusting the frequency from $f = 264.064$ to 264.066 kHz (1 Hz steps).

III. RESULTS AND DISCUSSION

We have measured the modulated transmission spectra of the HCF. Fig. 2(a) shows one predominant modulated notch in the spectrum, indicating that the variations of Δn_{eff} induced by MZ-2 are still negligible to generate multiple fringes. In this case, the two LPGs work as a unique grating with an induced phase shift caused mainly by the fixed length d [9]. The modulated notch approaches a nearly 2π -phase-shift at

$f_0 = 264.064$ kHz. Fig. 2(b) shows the modulated spectrum under an externally induced strain (d changes are estimated in about $\Delta d = 100$ μm). The modulated spectrum approaches a nearly π -phase-shift showing that the AOM has high sensitivity to monitor external measurands. Thus, minor variations of d changing the relative phase between the coupled modes might be useful to characterize strain in sensing applications.

In contrast, a multiwavelength spectrum is generated by increasing f to 264.065 kHz ($\Delta f = 1$ Hz) and 264.066 kHz ($\Delta f = 2$ Hz), as shown in Fig. 2(c) and 3(d). We note in the modulated spectra that increasing modal coupling and Δn_{eff} reduce the fringes FSR. This is caused by the frequency-tuning of MZ-2 edges curvatures coupling higher order modes. The reduced fringe FSR is followed by increasing fringes in the notch. The reduced fringe visibility (magnitude) in respect to the zero dB level implies that raising modal couplings might induce power losses (max. 2 dB). Overall, the fringe FSR could be tuned from FSR = 1 to 0.6 nm with a tuning slope of ~ 4 fringes/Hz (the spectra in Fig. 2(a) and 2(b) are not considered to estimate FSR).

Previous numerical and analytical studies show that the dual AOM-MZ couples favorably LP_{01} and higher order modes propagating in the HCF air core (predominantly the higher order modes LP_{11} and LP_{21}) [11]. These modes have a relevant spatial overlap of electric fields over the fiber cross-section, providing efficient modal couplings as described in [11]. Nevertheless, other modes with low spatial overlap, such as tube modes, might also couple in with minor modulation efficiency. Overall, the modulated spectra show a 3-dB notch bandwidth of ~ 4 nm and a maximum modulation depth of 6.5 dB at $\lambda_C \sim 1176$ nm for the considered frequencies. The modulated notch shows asymmetric fringe distribution around λ_C caused by variation of the modes Δn_{eff} and beatlengths in the considered spectral range [11].

In summary, the demonstrated AOM shows relevant high modulation efficiency employing a maximum 10 V drive voltage and a 7.5 cm short fiber length. This improved efficiency is caused by the increased induced strain in the HCF tubes changing the propagation mechanism of optical modes in the air core [11]. Thus, HCFs with large diameters might be suitably used to increase the acousto-optic interaction, reducing requirements of reduced diameter or long fibers, high drive voltages, and use of power amplification. The AOM-MZ is promising to characterize external measurands as strain, temperature, density, and viscosity by exposing the induced LPGs in contact with fluid substances, which might change the acoustic period and amplitude [2]. Further studies might also explore HCFs with larger air holes or thinner tubes with distinct fiber structures, adjusting the spectral modal properties to improve the FSR sensitivity, fringes visibility, and modulated spectrum symmetry.

IV. CONCLUSION

We experimentally demonstrate a new all-fiber acousto-optic dual MZ enabling full reconfiguration of a multiwavelength filter by frequency-tuning the FSR. MZ-1 is fabricated with a centered positioned acoustic driver inducing

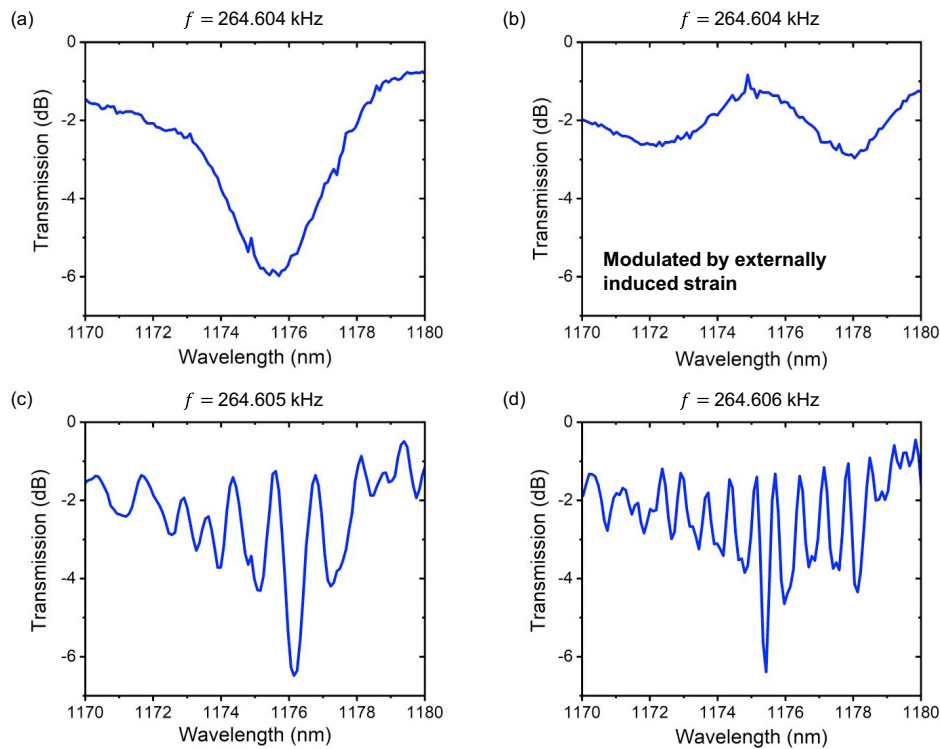


Fig. 2. Measured transmission spectra of the hollow core fiber for the frequency range of $f = 264.064 - 264.066$ kHz. (a) The AOM MZs induce a nearly 2π -phase-shift in the modulated spectrum at $f = 264.064$ kHz. (b) The spectrum is modulated by an externally induced strain resembling π -phase-shift. MZs multiwavelength spectra by tuning the fringes FSR with (c)(d) increasing frequency respectively in steps of $\Delta f = 1$ and 2 Hz.

simultaneously two acoustically induced LPGs. MZ-2 is formed by the attached HCF - driver length exciting two strong edge curvatures. The demonstrated AOM modulates a notch bandwidth of 4 nm with a maximum depth of 6.5 dB at 1176 nm. FSR is tuned from 1 to 0.6 nm by changing the frequency in steps of 1 and 2 Hz. Thus, the AOM-MZ provides high frequency-tuning sensitivity dynamically generating from 1 to 8 resonant wavelengths, due to increased modal couplings and Δn_{eff} . In addition, the preliminary results indicate high sensitivity to measure strain induced by external measurands. This sensitivity might be studied to measure temperature, density, refractive index, and viscosity by exposing the device to fluid substances [2]. Overall, the modulated notch width, fringe number, and FSR show a strong dependence on the induced HCF modal couplings, which can be adjusted by optimizing the HCF structure. The demonstrated AOM-MZ provides compactness, high modulation efficiency, and an in-line monolithic fiber setup, which is suitable for tunable filters and fiber sensors.

REFERENCES

- [1] H. Qian *et al.*, "Fiber-optic viscometer with all-fiber acousto-optic superlattice modulated structure," *Journal of Lightwave Technology*, vol. 36, no. 18, pp. 4123–4128, Sep. 2018, doi: 10.1109/JLT.2018.2859239.
- [2] R. A. Oliveira, J. Canning, K. Cook, M. Nashqbandi, and A. A. P. Pohl, "Compact dip-style viscometer based on the acousto-optic effect in a long period fiber grating," *Sens Actuators B Chem*, vol. 157, no. 2, pp. 621–626, Oct. 2011, <http://dx.doi.org/10.1016/j.snb.2011.05.035>
- [3] J. H. Osório *et al.*, "High sensitivity LPG Mach-Zehnder sensor for real-time fuel conformity analysis," *Meas Sci Technol*, vol. 24, no. 1, p. 015102, Dec. 2012, doi: 10.1088/0957-0233/24/1/015102.
- [4] J. F. Ding, A. P. Zhang, L. Y. Shao, J. H. Yan, and S. He, "Fiber-taper seeded long-period grating pair as a highly sensitive refractive-index sensor," *IEEE Photonics Technology Letters*, vol. 17, no. 6, pp. 1247–1249, Jun. 2005, doi: 10.1109/LPT.2005.847437.
- [5] P. Caldas and G. Rego, "Optical Fiber Interferometers Based on Arc-Induced Long Period Gratings at INESC TEC," *Sensors* 2021, vol. 21, no. 21, p. 7400, Nov. 2021, doi: 10.3390/S21217400.
- [6] Y. Ma *et al.*, "A Mach-Zehnder interferometer with two V-shaped cores for refractive index sensing," *Sens Actuators A Phys*, vol. 351, p. 114189, Mar. 2023, doi: 10.1016/J.SNA.2023.114189.
- [7] T. Wei, X. Lan, and H. Xiao, "Fiber inline core-cladding-mode Mach-Zehnder interferometer fabricated by two-point CO₂ laser irradiations," *IEEE Photonics Technology Letters*, vol. 21, no. 10, pp. 669–671, May 2009, doi: 10.1109/LPT.2009.2016116.
- [8] M. Shao, X. Qiao, H. Fu, N. Zhao, Q. Liu, and H. Gao, "An in-fiber mach-zehnder interferometer based on arc-induced tapers for high sensitivity humidity sensing," *IEEE Sens J*, vol. 13, no. 5, pp. 2026–2031, 2013, doi: 10.1109/JSEN.2013.2247591.
- [9] L. Zhong *et al.*, "Reconfigurable ultra-broadband mode converter based on a two-mode fiber with pressure-loaded phase-shifted long-period alloyed waveguide grating," *Optics Express*, vol. 31, no. 5, pp. 8286–8295, Feb. 2023, doi: 10.1364/OE.480362.
- [10] R. E. da Silva *et al.*, "All-fiber broadband spectral acousto-optic modulation of a tubular-lattice hollow-core optical fiber," *Optics Letters*, vol. 49, no. 3, pp. 690–693, Feb. 2024, doi: 10.1364/OL.512222.
- [11] R. E. da Silva *et al.*, "Highly efficient interaction of a tubular-lattice hollow-core fiber and flexural acoustic waves: design, characterization and analysis," Feb. 2024. Available: <https://arxiv.org/abs/2402.15825v1>
- [12] S. Kang, H. Zhang, B. Liu, N. Zhang, and Y. Miao, "Acousto-optic fiber interferometer based on concatenated flexural wave modulation," *Optics Express*, vol. 54, no. 7, p. 076106, Jul. 2015, doi: 10.1117/1.OE.54.7.076106.
- [13] F. Amrani *et al.*, "Low-loss single-mode hybrid-lattice hollow-core photonic-crystal fibre," *Light: Science & Applications* 2021 10:1, vol. 10, no. 1, pp. 1–12, Jan. 2021, doi: 10.1038/s41377-020-00457-7.
- [14] E. C. Silva-Alvarado *et al.*, "Tunable filter based on two concatenated symmetrical long period fiber gratings as Mach-Zehnder interferometer and its fiber lasing application," *Opt Laser Technol*, vol. 149, p. 107824, May 2022, doi: 10.1016/J.OPTLASTEC.2021.107824.