



HAL
open science

Ultra-thin endoscopes: two-photon imaging at the tip of a bare fiber with wavefront shaping

Fatima El Moussawi, Matthias Hofer, Siddharth Sivankutty, Luca Genchi, Damien Labat, Andy Cassez, Geraud Bouwmans, Rosa Cossart, Olivier Vanvincq, Hervé Rigneault, et al.

► To cite this version:

Fatima El Moussawi, Matthias Hofer, Siddharth Sivankutty, Luca Genchi, Damien Labat, et al.. Ultra-thin endoscopes: two-photon imaging at the tip of a bare fiber with wavefront shaping. 2024 24th International Conference on Transparent Optical Networks (ICTON), Jul 2024, Bari, France. pp.1-4, 10.1109/ICTON62926.2024.10648136 . hal-04793198

HAL Id: hal-04793198

<https://hal.science/hal-04793198v1>

Submitted on 20 Nov 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.

Ultra-thin endoscopes: two-photon imaging at the tip of a bare fiber with wavefront shaping

Fatima El Moussawi¹, Matthias Hofer², Siddharth Sivankutty¹, Luca Genchi², Damien Labat¹,
Andy Cassez¹, Geraud Bouwmans¹, Rosa Cossart³, Olivier Vanvincq¹, Herve Rigneault²,
Esben Ravn Andresen¹

1. Univ. Lille, CNRS, UMR 8523 - PhLAM - Physique des Lasers Atomes et Molécules, F-59000, Lille

2. Aix-Marseille University, CNRS, Centrale Marseille, Institut Fresnel, F-13013 Marseille, France

3. Aix Marseille University, INSERM, INMED, Turing Center for Living Systems, F-13273 Marseille, France

E-mail: siddharth.sivankutty@cnrs.fr, esben.andresen@univ-lille.fr

ABSTRACT

In this letter, we will explore the utilization of specialty multi-core fibers combined with wavefront shaping to enable two-photon imaging using femtosecond pulses. Specifically, we will emphasize the optimization of both the design and the post-processing of these multi-core fibers to achieve a compact footprint (200 microns), efficient power delivery, and resilience to mechanical perturbations

Keywords: multicore fibers, imaging, adaptive optics, coherent combining

1. INTRODUCTION

Imaging with cellular resolution through biological tissue remains a longstanding challenge. In this context, endoscopes based on optical fibers have emerged as a means to image deep inside living organisms. However, this ability comes at the expense of the invasive nature of the probe. Therefore, it is interesting to develop methods that minimize the probe's footprint and eliminate active elements to ensure the safety of the organism under test. Lensless endoscopes based on optical fibers — a concept pioneered in the last decades — represent a class of techniques pursuing extreme miniaturization, leading to probes fundamentally limited by the size of the fiber. In this paper, we examine how a combination of specialty multi-core fibers and spatial light modulators addresses the specific challenge of performing 3D resolved nonlinear imaging.

2. NONLINEAR IMAGING THROUGH MULTICORE FIBERS

The overarching concept behind nonlinear imaging through a bare fiber is presented below in Figure 1.

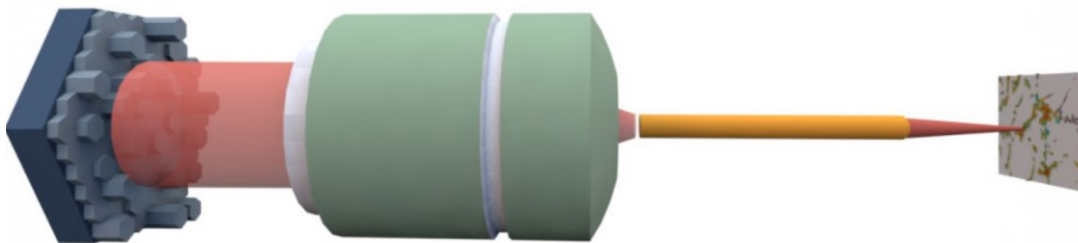


Figure 1 A conceptual sketch of a lensless endoscope. The main elements, a spatial light modulator (blue), the arbitrary optical system represented as a lens (green) and the fiber (yellow). The electric field at the distal end of the fiber can be fully controlled and shaped by the spatial light modulator at the proximal end. This enables focusing and scanning a laser beam; performing point scanning imaging analogous to a confocal microscope

A lensless endoscope relies on optical fibers (either multimode (MMF) or multicore fibers (MCF)) to transmit the image from its distal tip to the proximal end [1]. However, this process is often obstructed by mode mixing in the fibers, which distorts the image when accessed at the proximal end. Since 2010, efforts have surged to invert this process of mode-scrambling, either physically or numerically. Physical approaches leverage the fact that for coherent transport through the fibers, even in the case of strong mode-mixing, the image information is not lost but merely scrambled [2]. Adopting the transmission matrix framework, one can measure the transmission matrix of any fiber (MMF or MCF) and recover the image information [3]. Using this powerful conceptual tool, we tackle the problem of performing nonlinear imaging at the tip of an ultra-thin fiber probe. This entails addressing three main challenges: (i) delivering a femtosecond pulse through a fiber, (ii) focusing and scanning the laser beam with no opto-mechanical elements at the distal end, and (iii) efficiently collecting the fluorescence signal.

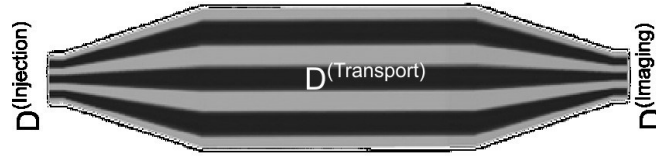


Figure 2 A sketch of the tapered MCF. The original MCF is designed with large inter-core distances and the size of each core (D) is optimized to have minimal inter-core group delay dispersion. The injection and imaging ends are then tapered down

2.1 Multicore fibers as a key enabling technology

While there have been demonstrations of MMFs in lensless endoscopes employing nonlinear contrast [4], they have limitations in focusing the laser at the distal end. This arises due to the significant differential mode delay, even when employing graded-index fibers. In earlier works, we have demonstrated that multicore fibers employing single mode cores suffer minimal inter core group delay dispersion [1], and hence are more suited for the delivery of femtosecond pulses through a few tens of centimetres of the fiber. In addition to this, we have addressed two other main challenges by engineering the properties of the MCF. The first demonstration was the development of a helically twisted multicore fiber, that ensured the endoscope is impervious to any bending or mechanical perturbations [5], and the second demonstration employed an optimized spatial distribution of the single mode cores to ensure both the imaging metrics: i) resolution and ii) field of view, are limited only by diffraction itself [6], [7]. Despite these advantages, generating an intense spatio-temporal focus at the distal tip remains a major challenge. This arises from using a sparse layout of the cores along the face of the MCF (~475 cores over a 330 μm diameter). While this layout has favourable characteristics such as low cross-talk and an infinite memory effect [1], it effectively delivers only a few percent of the total power into the central focal spot, quantified by the strehl ratio [8]. Thus, there is a conflict between the parameters required for delivering ultrashort pulses (sparse cores) and imaging performance (dense layout) [1]. In [9], we increased the strehl ratio by 3D printing a hyper-telescope utilizing a femtosecond laser. In this contribution, we present an alternative approach to artificially increase the mode density at the distal end of the fiber by tapering the fiber itself, as illustrated in Figure 2.[8]

2.2 Tapered multicore fibers

We utilized a framework based on coupled-mode theory (CMT) and perturbation theory to identify the optimal parameters for the tapered MCF and simulate its imaging performance in the far field at the distal end [8]. Briefly, we considered the tapered fiber as a series of uniform segments whose structural parameters needed optimization. CMT was used to compute the effective indices of the guided modes at each segment and hence its complex transmission matrix, H , expressed in the basis of the guided modes of each segment. The transmission matrix of the entire fiber, H , is expressed as a product of the transmission matrices of the individual segments. This framework allows us to predict both the cross-talk between the cores and the expected strehl ratio. We compare the cross-talk matrix from this model to the gold standard, the finite element method, and observe agreement in Figure 3a for taper ratios of interest. While the CMT model is extremely fast, requiring less than a minute, its validity is limited to the weakly coupled regime. In our case, this corresponds to a taper ratio of about 0.5. Nevertheless, its speed enables quick identification and iterative optimization of fiber parameters such as core size, inter-core distances, and taper ratios. As a first step, we address pulse broadening in the fiber, which largely results from local variation of the single-mode cores. Generally, the inter-core group delay dispersion for the fundamental mode decreases with an increasing V -parameter of the core. Figure 3b, indicates the calculated values for a step-index and parabolic index core, and we chose to fabricate a MCF that a parabolic index profile and a core size such that it operates at the second cut-off ($V = 5.06$). This required tapering the injection end (proximal) of the fiber over a short distance (2 mm) to ensure coupling only into the fundamental mode in the transport region of the MCF.[8]

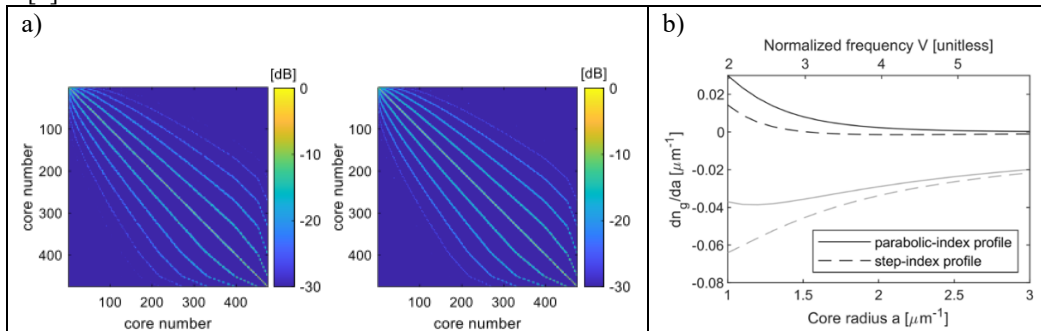


Figure 3 Panel (a) A comparison of the crosstalk matrix of a uniform 475 core MCF with a pitch of 7.5 μm simulated with the CMT model (left) and the FEM model (right). Panel (b) is the calculated derivative of the group delays for a step-index and parabolic fiber

2.3 Experimental results

Once the design parameters for the untapered MCF and the required taper ratios were identified, the fiber was fabricated at FiberTech, Lille using the conventional stack and draw technique. The fibers were then tapered with a transition length of 2 mm and post-processed with a CO₂ laser based glass processing station (LZM-100, Fujikura) Characteristic scanning electron microscope images of the tapered fibers and their parameters are indicated in Fig 4.

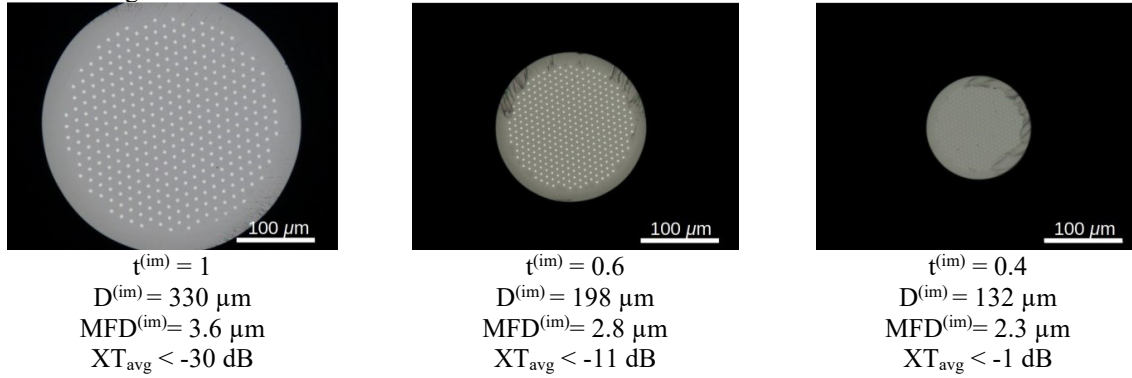


Figure 4 A summary of the experimental parameters of the tapered fiber. The distal ends (imaging end) of the fibers for taper ratios [1,0.6,0.4] are depicted with the experimentally measured mode field diameters (MFD) and the average crosstalk (XT). All the images are made on the same spatial scale. The superscript (im) indicates the imaging end of the MCF

The improved strehl ratios and the resulting memory effect were experimentally characterized using an optical test bench with a spatial light modulator and a camera at the distal end of the MCF. For a more detailed description of the setup, we refer the readers to [7], [8]. We observe an increase of the strehl ratio from 0.07 for the un-tapered fiber ($t^{(im)} = 1$) to 0.19 for a tapered fiber ($t^{(im)} = 0.4$) (see Fig 5 (left panel)). Since, the two photon excited fluorescence signal is proportional to the square of the intensity of the focused spot, we expect a quadratic increase in the SNR. In practise, we measure a signal larger by a factor 6. We do observe a discrepancy for the expected values of the improvement in the strehl ratio at the ($t^{(im)} = 0.4$), as our assumptions of a weakly coupled regime are no longer valid. This is also reflected in the plot of the measured memory effects for different taper ratios in the right panel of Figure 3. This indicates that a simple linear tilts at the proximal end of the fiber with the SLM no longer results in a tilt of the composite wavefront at the distal end.

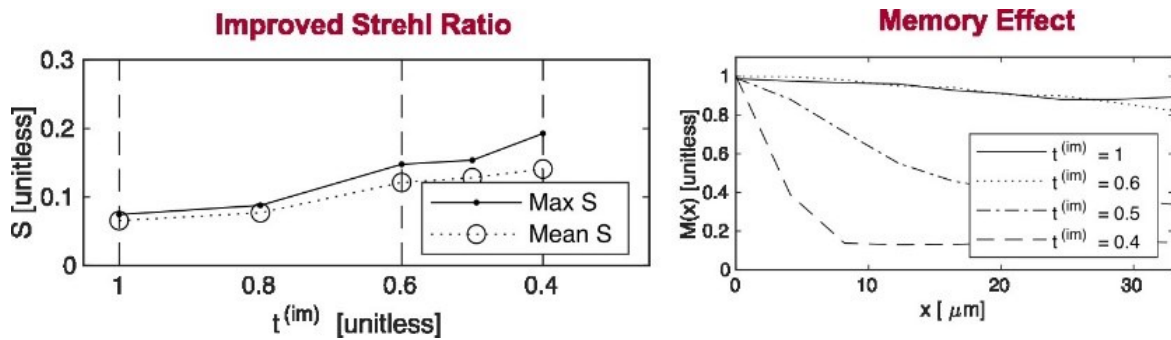


Figure 5 Measurements of the strehl ratio (left) and the memory effect (right) for the tapered fibers

Finally, we used the same setup to perform two-photon imaging on a biological sample (excitation wavelength at 920 nm) with a tapered MCF ($t^{(im)} = 0.6$). After an initial measurement of the transmission matrix, we focus and scan the laser at the distal end to perform point-scanning imaging. A set of wavelength filters in front of a single pixel detector ensures that we collect only the generated fluorescence signal and not the laser itself. The resulting images are depicted in Figure 6. The increased focusing efficiency allows us to generate a 2 photon image of a sample with a conventional laser source (1 Watt average power, 80 MHz, Ti:Sapphire) while earlier demonstration relied on high pulse energy sources and complex calibration techniques to mitigate inter-core group delay dispersion [10]. Nevertheless, we observe artifacts in the images (replicas of the central motif). This can be alleviated by using a fiber with an optimized core layout as in [6]

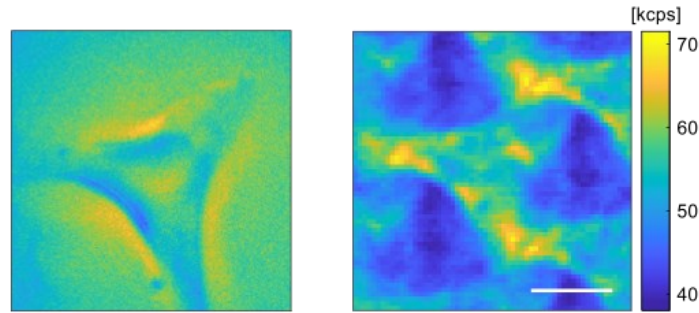


Figure 6 The ground truth image (left) and the two-photon image from the lensless endoscope (right). Note that there are periodic artifacts in the lensless endoscope image arising from the periodic arrangement of the core.

3. CONCLUSIONS AND PERSPECTIVES

We have reported the conception and fabrication of a tapered MCF for nonlinear lensless endoscopy and its proof of principle application to imaging a biological sample. We see a significant improvement of a factor 6 in the generated fluorescence signal. In the future, the tapering would be employed in conjunction with twisted fibers, aperiodic core layouts and a double clad geometry. This would address the limitations of these initial demonstrations, and pave the way to a high-efficiency and bending-insensitive lensless endoscope capable of imaging at the cellular resolution.

ACKNOWLEDGEMENTS

Parts of this work were developed at IRCICA (USR CNRS 3380, <https://ircica.univ-lille.fr/>) using FiberTech Lille facilities (<https://fibertech.univ-lille.fr/en/>). This work was supported by the French Ministry of Higher Education and Research, the "Hauts de France" Regional Council, the European Regional Development fund (ERDF) through the CPER "Photonics for Society

REFERENCES

- [1] E. R. Andresen, S. Sivankutty, V. Tsvirkun, G. Bouwmans, and H. Rigneault, 'Ultrathin endoscopes based on multicore fibers and adaptive optics: A status review and perspectives', *J. Biomed. Opt.*, vol. 21, no. 12, 2016, doi: 10.1117/1.JBO.21.12.121506.
- [2] S. M. Popoff, G. Lerosey, R. Carminati, M. Fink, A. C. Boccara, and S. Gigan, 'Measuring the Transmission Matrix in Optics: An Approach to the Study and Control of Light Propagation in Disordered Media', *Phys. Rev. Lett.*, vol. 104, no. 10, Mar. 2010, doi: 10.1103/PhysRevLett.104.100601.
- [3] T. Čižmár and K. Dholakia, 'Shaping the light transmission through a multimode optical fibre: complex transformation analysis and applications in biophotonics', *Opt. Express*, vol. 19, no. 20, p. 18871, Sep. 2011, doi: 10.1364/OE.19.018871.
- [4] S. Sivankutty, E. R. Andresen, R. Cossart, G. Bouwmans, S. Monneret, and H. Rigneault, 'Ultra-thin rigid endoscope: Two-photon imaging through a graded-index multi-mode fiber', *Opt. Express*, vol. 24, no. 2, pp. 825–841, 2016, doi: <https://dx.doi.org/10.1364/OE.24.000825>.
- [5] V. Tsvirkun *et al.*, 'Flexible lensless endoscope with a conformationally invariant multi-core fiber', *Optica*, vol. 6, no. 9, pp. 1185–1189, Sep. 2019, doi: 10.1364/OPTICA.6.001185.
- [6] S. Sivankutty *et al.*, 'Extended field-of-view in a lensless endoscope using an aperiodic multicore fiber', *Opt. Lett.*, vol. 41, no. 15, pp. 3531–3534, 2016, doi: 10.1364/OL.41.003531.
- [7] S. Sivankutty, V. Tsvirkun, O. Vanvincq, G. Bouwmans, E. R. Andresen, and H. Rigneault, 'Nonlinear imaging through a Fermat's golden spiral multicore fiber', *Opt. Lett.*, vol. 43, no. 15, pp. 3638–3641, 2018, doi: 10.1364/OL.43.003638.
- [8] F. El Moussawi *et al.*, 'Tapered Multicore Fiber for Lensless Endoscopes', *ACS Photonics*, vol. 9, no. 8, pp. 2547–2554, Aug. 2022, doi: 10.1021/acsp Photonics.2c00661.
- [9] S. Sivankutty *et al.*, 'Miniature 120-beam coherent combiner with 3D-printed optics for multicore fiber-based endoscopy', *Opt. Lett.*, vol. 46, no. 19, p. 4968, Oct. 2021, doi: 10.1364/OL.435063.
- [10] D. B. Conkey, N. Stasio, E. E. Morales-Delgado, M. Romito, C. Moser, and D. Psaltis, 'Lensless two-photon imaging through a multicore fiber with coherence-gated digital phase conjugation', *J. Biomed. Opt.*, vol. 21, no. 4, p. 045002, Apr. 2016, doi: 10.1117/1.JBO.21.4.045002.