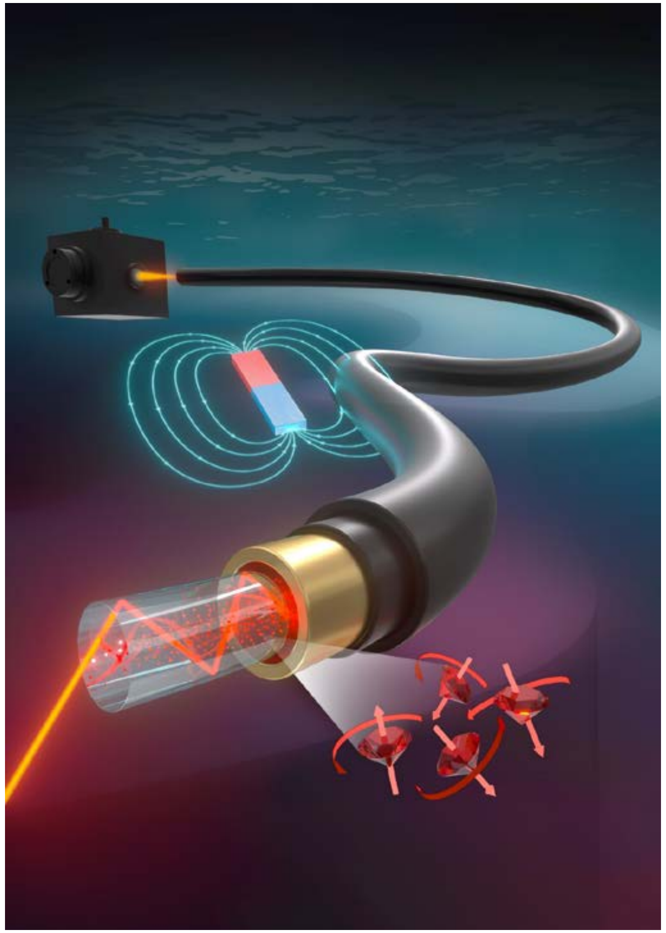
Volumetric integration of nanodiamonds in optical fiber cores

Ryszard Buczyński, Adam Filipkowski, Mariusz Mrózek, Grzegorz Stępniewski, Maciej Głowacki, Mateusz Ficek, Dariusz Pysz, Wojciech Gawlik, Robert Bogdanowicz, Adam Wojciechowski, Mariusz Klimczak

UNIVERSITY OF WARSAW
JAGIELLONIAN UNIVERSITY IN KRAKÓW
GDAŃSK UNIVERSITY OF TECHNOLOGY
Łukasiewicz

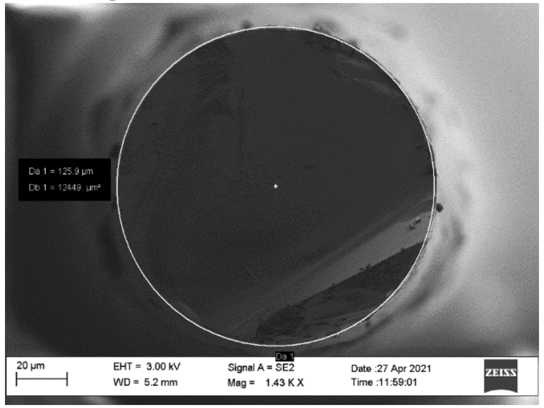


European Funds Smart Growth
FNP Foundation for Polish Science
European Union European Regional Development Fund

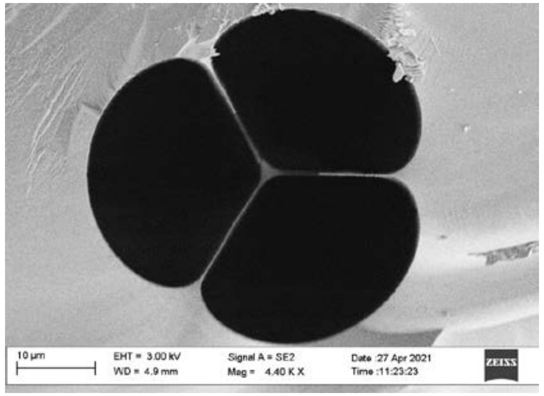
QUNNA
www.qunna.pl

Agenda

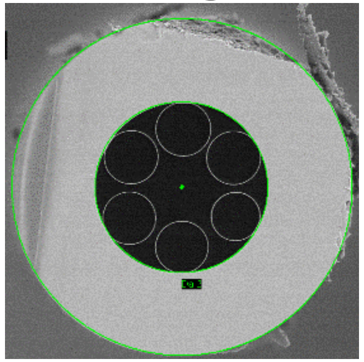
I. Optical fibers with with NV nanodiamonds: magnetometry



1. Step-index multimode fiber

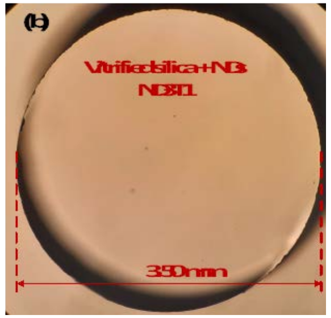


2. Step-index suspended core microstructured fiber

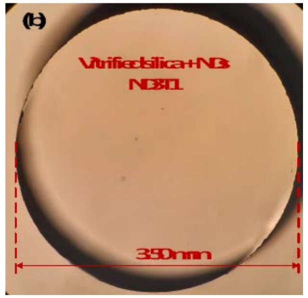


3. Hollow-core anti-resonant fiber

II. Optical fibers with nanodiamonds: reduction of nonlinearity



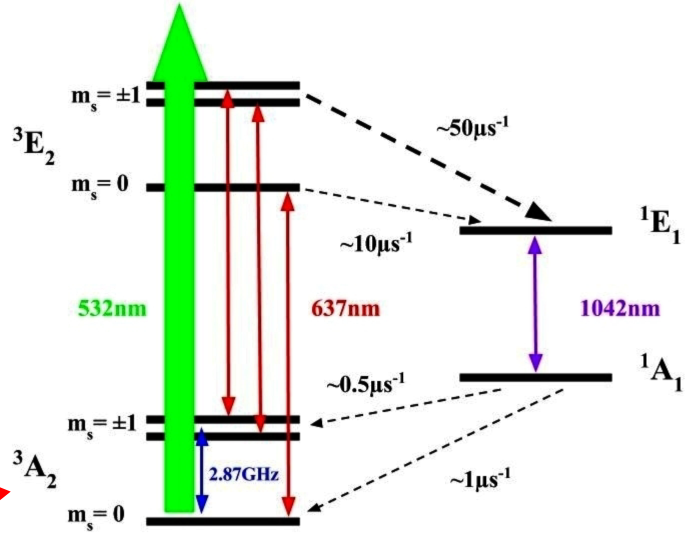
2. Step index fiber based on F2 glass with NDs



2. Vitrified silica glass with NDs

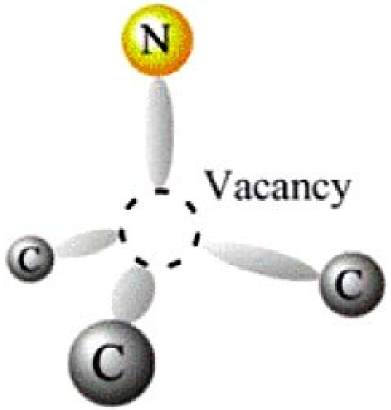
Magnetic field sensing with NV nanodiamonds

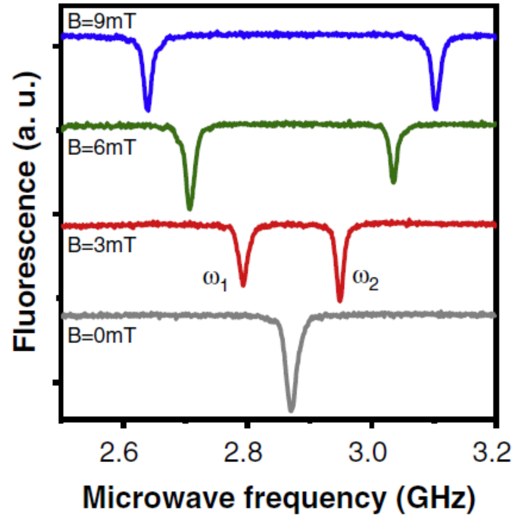
Conduction band



Valence band

Spin polarization
of the ground state





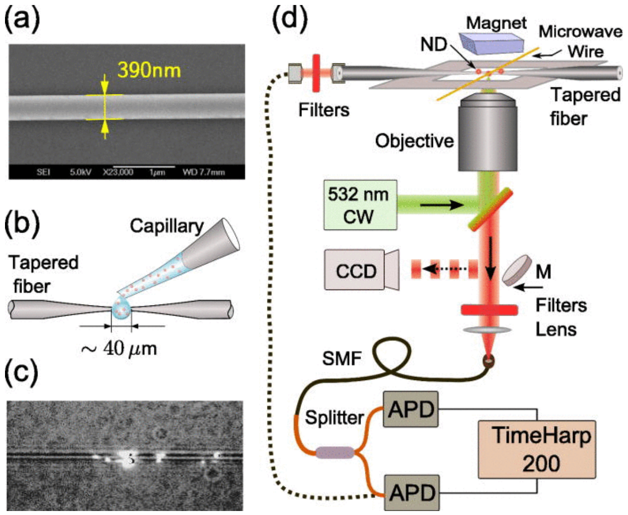
- **Efficient fluorescence collection requires integration of NDs with specific platforms**
- **Optical pumping: population transfer from |±1⟩ to |0⟩**
- **Optical readout: Optically Detected Magnetic Resonance (ODMR)**

- **OPTICAL probing and readout of ND state can benefit from the integration with optical fibers**

Nanodiamond integration with optical fibers – the state of the art

Optical fiber tapers
(evanescent field operation)

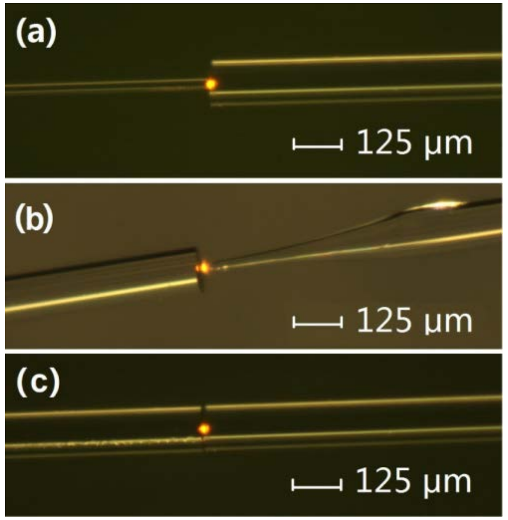
Xiaodi Liu et al. Appl. Phys. Lett. 103, 143105 (2013)



Fiber tip functionalization

T. Schröder et al. Optics Express 20, 10490 (2012)

D. Duan et al. Optics Express 27, 6734 (2019)



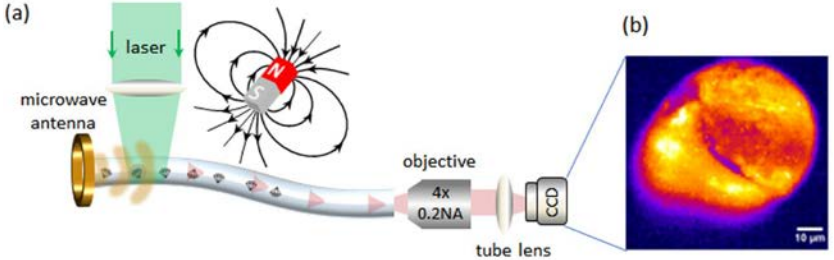
Both approaches: ultra-precise, but highly localized interaction with monitored object / field

Diamond particle-doped glass & optical fiber

- *Doping* of diamond particles into glass and drawing into fibers:
  magnetically sensitive optical fibers - 2014 & on: **prof. H. Ebendorff-Heidepriem & group, The University of Adelaide**

What for? + advantages

- Magnetically sensitive endoscopes for remote B-field sensing
- Immobilization and protection of diamonds
- Improvement of NV *fluorescence collection* efficiency



SCIENTIFIC REPORTS **2017**

OPEN

Magnetically sensitive nanodiamond-doped tellurite glass fibers

Received: 17 August 2017
Accepted: 22 December 2017
Published online: 19 January 2018

Yinlan Ruan[1], David A. Simpson[2], Jan Jeske[3], Heike Ebendorff-Heidepriem[1], Desmond W. M. Lau[4], Hong Ji[1], Brett C. Johnson[5], Takeshi Ohshima[6], Shahraam Afshar V.[1,7], Lloyd Hollenberg[2,5], Andrew D. Greentree[4], Tanya M. Monro[1,7] & Brant C. Gibson[4]

Limitations

- Survivability of diamonds at fiber-drawing temperatures
- Scattering loss at diamond particles

Solutions

- Soft glasses drawable into fibers at 400-700 deg.C
  (i) Mixing diamonds into raw materials and melting glass - tellurite fibers
  (ii) Dip-coating preforms and drawing into fibers - lead-silicate glass fibers
- Structure modifications i.e. ring-shaped area of core doped with diamonds

Nanodiamond in tellurite glass Part II: practical nanodiamond-doped fibers

Yinlan Ruan,[1] Hong Ji,[1] Brett C. Johnson,[2] Takeshi Ohshima,[3] Andrew D. Greentree,[4] Brant C. Gibson,[4] Tanya M. Monro[1] and Heike Ebendorff-Heidepriem[1*]

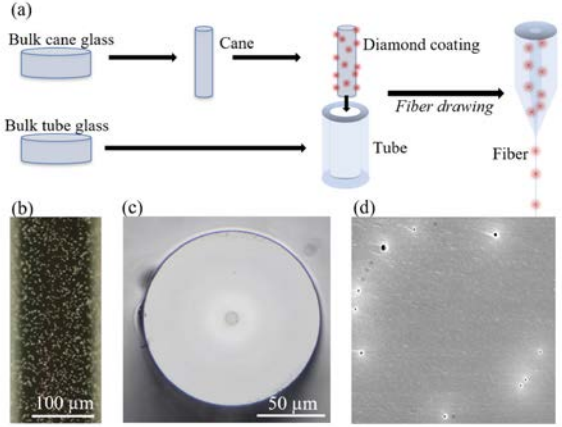
2014

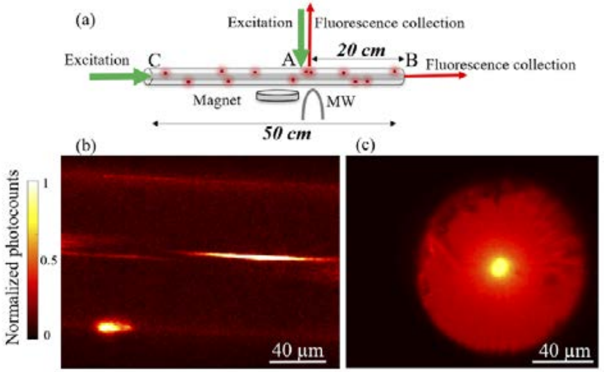
Fluorescent diamond microparticle doped glass fiber for magnetic field sensing

Cite as: APL Mater. 8, 081102 (2020); https://doi.org/10.1063/5.0013473
Submitted: 12 May 2020 . Accepted: 21 July 2020 . Published Online: 03 August 2020

D. Bai, M. H. Huynh, D. A. Simpson, P. Reineck, S. A. Vahid, A. D. Greentree, S. Foster, H. Ebendorff-Heidepriem, and B. C. Gibson

2020





Results

- Guiding of NV fluorescence over fiber sections ~50 cm long
- < 1 μT√Hz magnetic field sensitivity in ODMR measurements

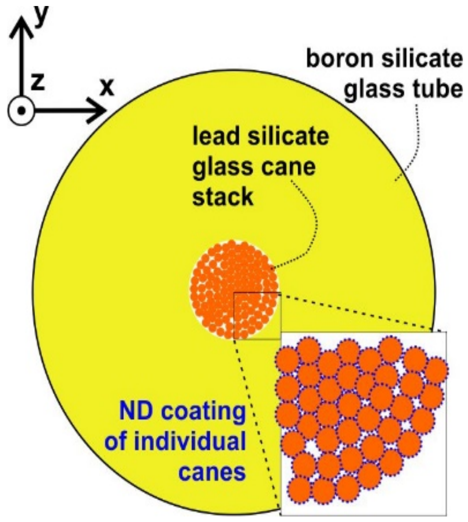
Our approach

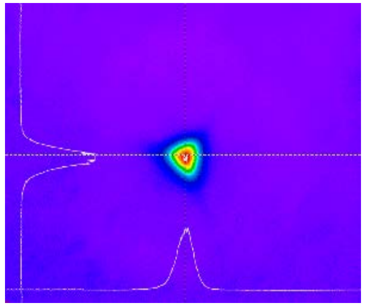
What do we do?

volumetric incorporation of NV diamonds in the fiber core

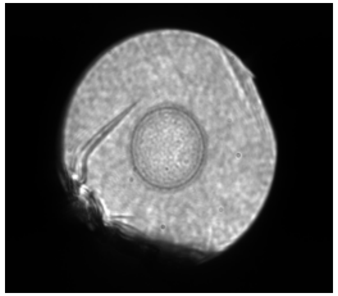
Why is it important?

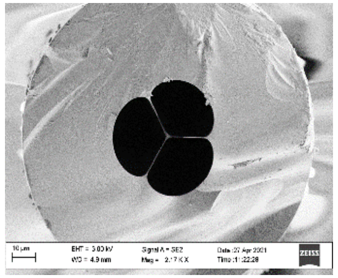
- Enables scaling of concentration
- Enables distributed sensing
- Does not sacrifice magnetic response?

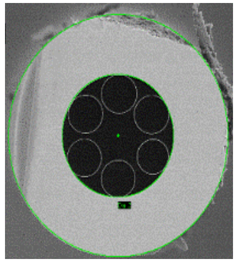




- **Different fiber geometries enable addressing coupling effciency of NV⁻ to guided modes**



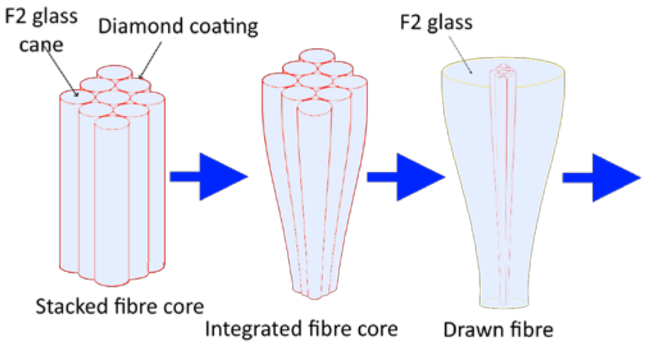


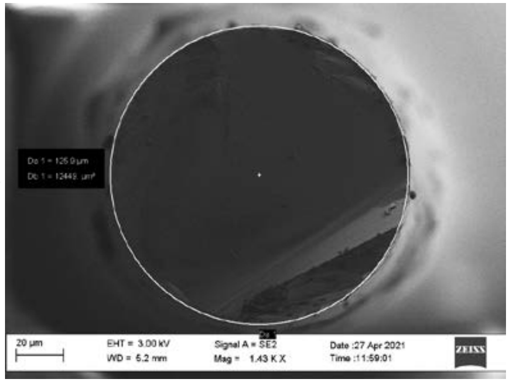


Our approach

How do we do it?

1. dip coating of glass preform components in ND liquid suspensions

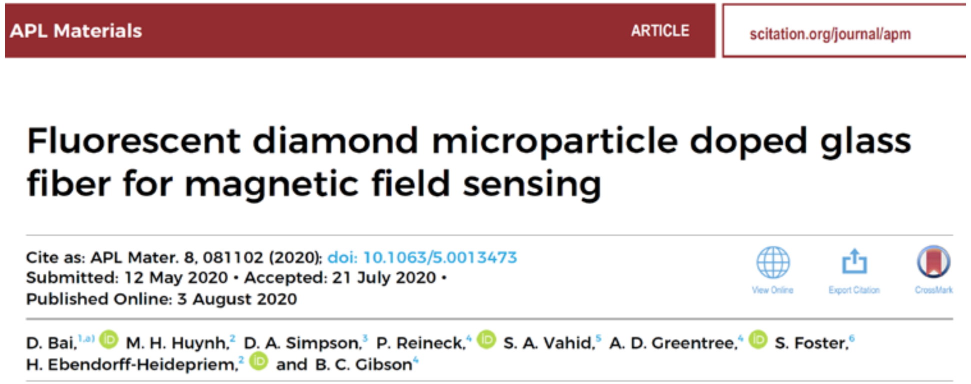




Dip-coating of fiber preforms and drawing into fibers

- limited to single-ring topology

D. Bai et al., APL Mater. 8, 081102 (2020);

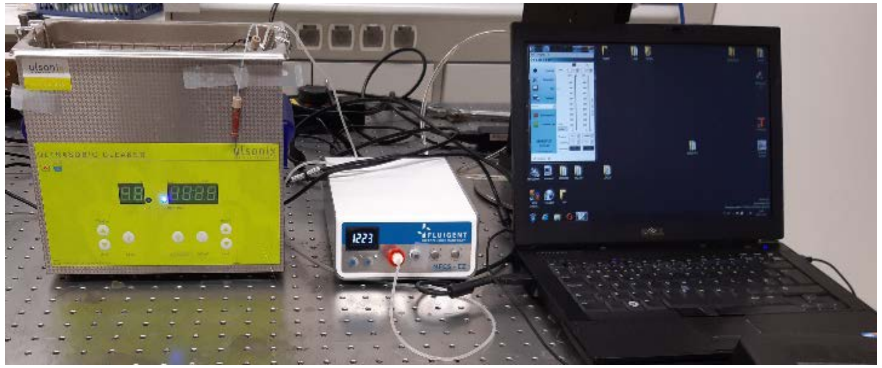

APL Materials ARTICLE scitation.org/journal/apm

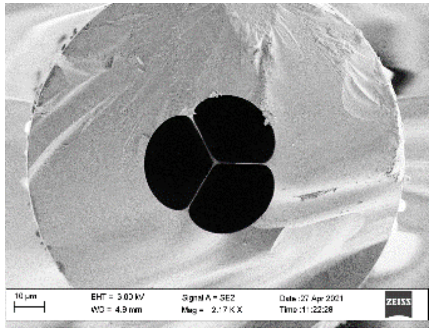
Fluorescent diamond microparticle doped glass fiber for magnetic field sensing

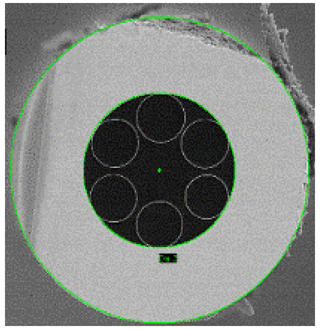
Cite as: APL Mater. 8, 081102 (2020); doi: 10.1063/5.0013473
Submitted: 12 May 2020 • Accepted: 21 July 2020 •
Published Online: 3 August 2020

D. Bai,[1,a] M. H. Huynh,[2] D. A. Simpson,[3] P. Reineck,[4] S. A. Vahid,[5] A. D. Greentree,[4] S. Foster,[6] H. Ebendorff-Heidepriem,[2] and B. C. Gibson[4]

2. infiltration of hollow core fibers with ND liquid suspensions



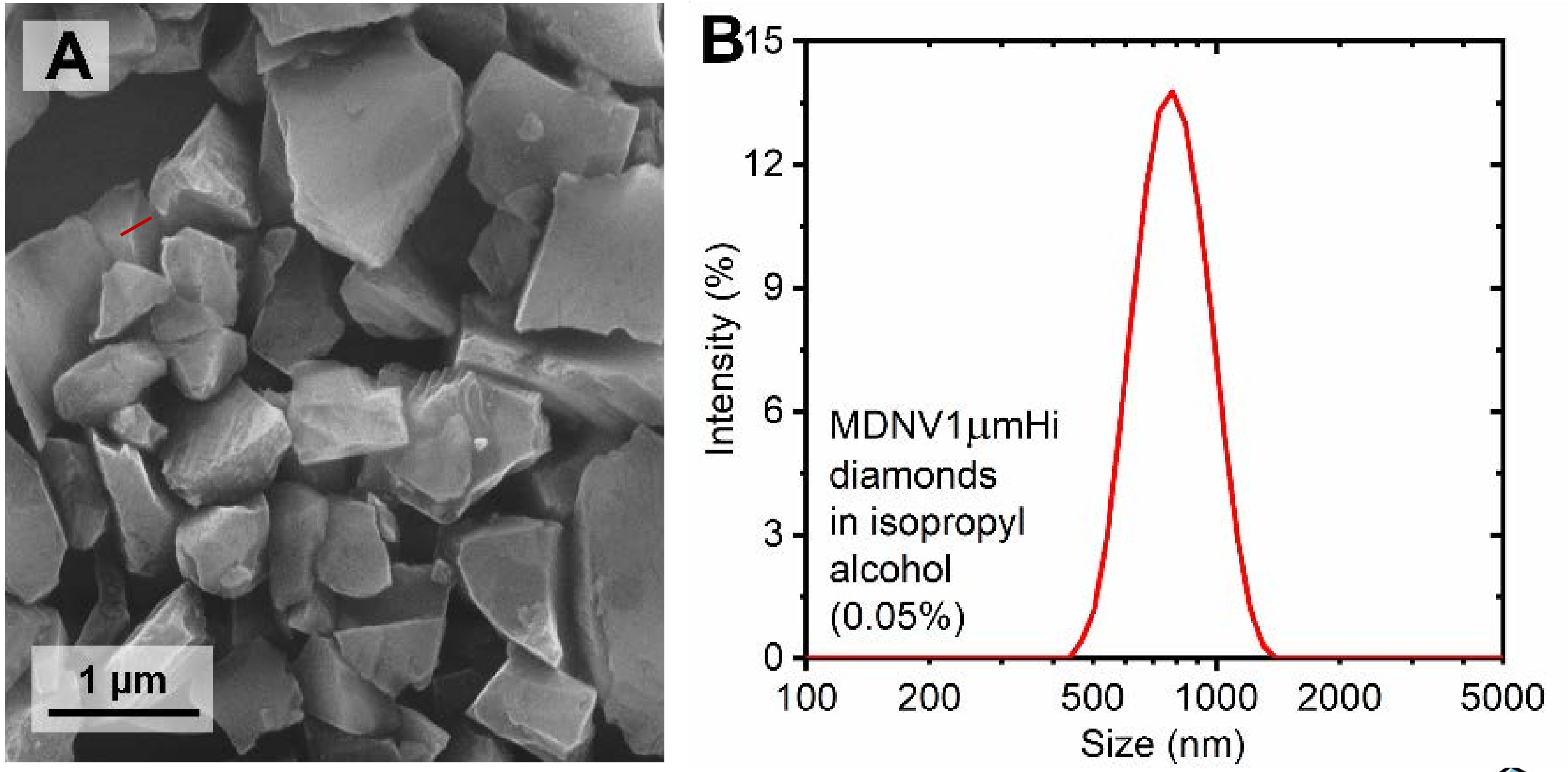




The ND deposited by infiltrating the core with IPA suspension followed by drying and flushing with pristine IPA.

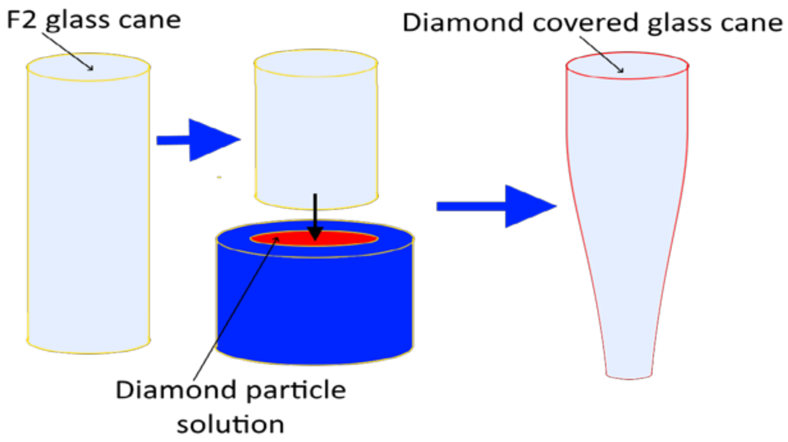
Diamond particles for integration with glass

MDNV1um, Adámas Nanotechnologies
(developed using HPHT by vendor)
Mean particle size 750 nm
measured with the dynamic light scattering method

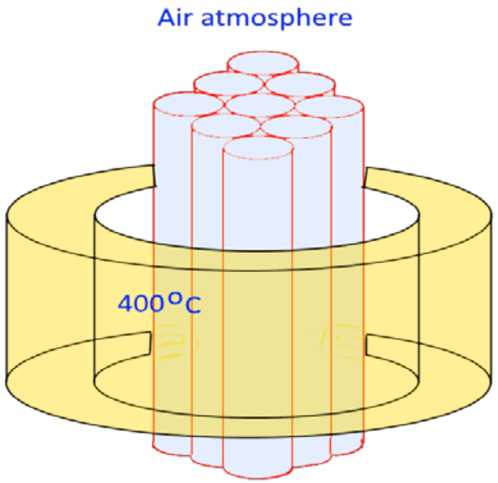


1. The step-index fiber

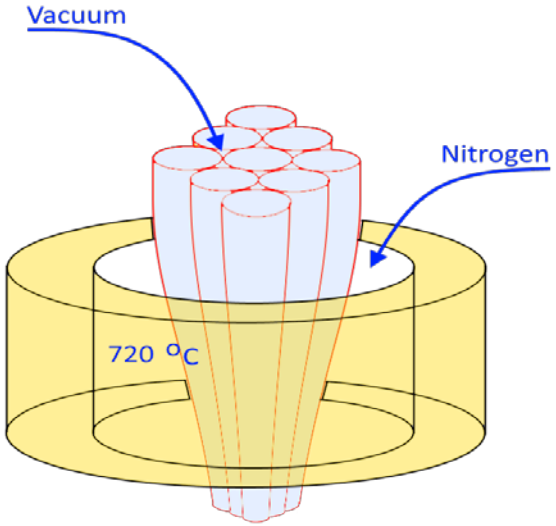
1.

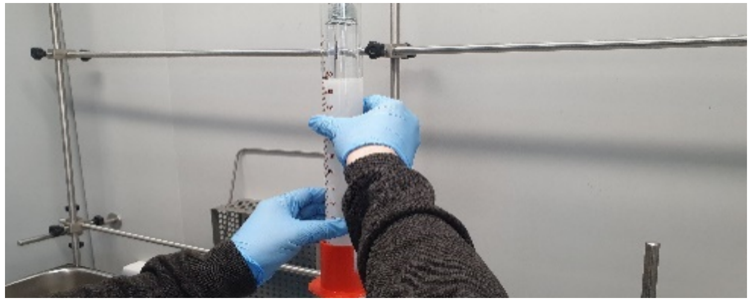


2.



3.





Nanodiamonds used:

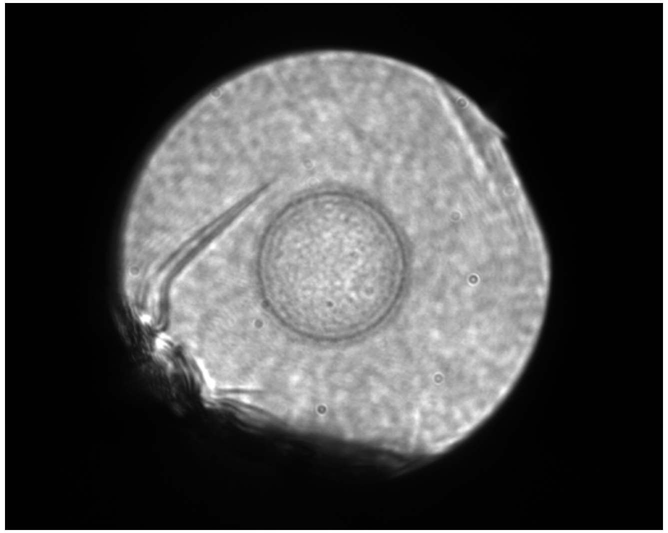
- **MDNV1um, Adámas Nanotechnologies ,**
- NV concentration 3.5 ppm

Fibre core:

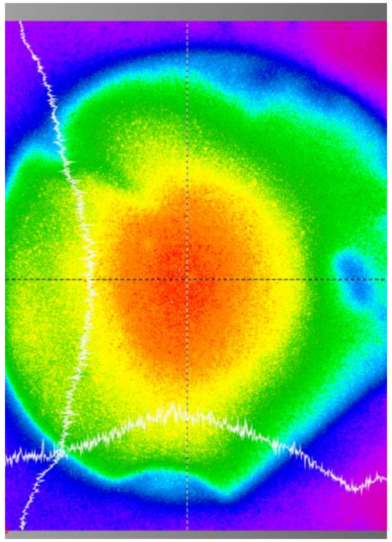
- stacked using 790 glass rods
- coated with MD-NV-1um-Hi nanodiamonds 750 nm in size
- Schott F2 glass
- Low-index F2 modification for cladding tube

1. The step-index fiber

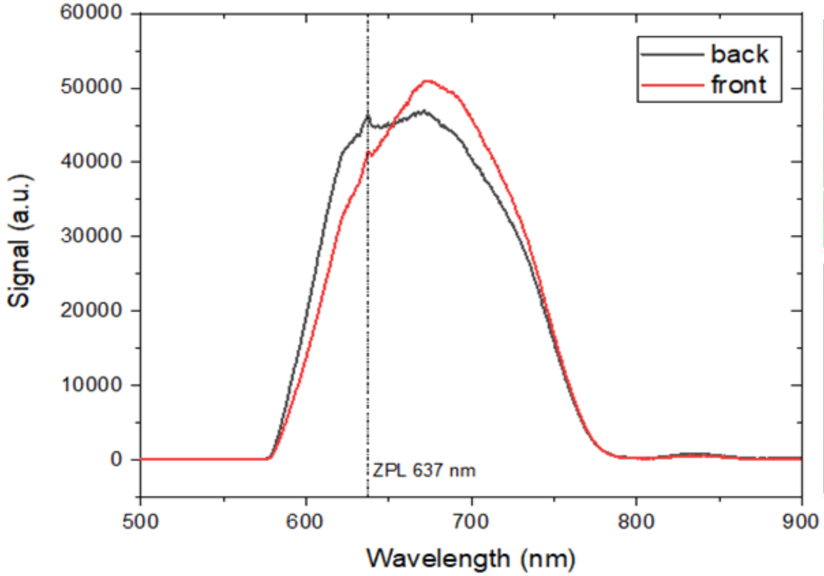
Cross-section of the fabriacted fibre



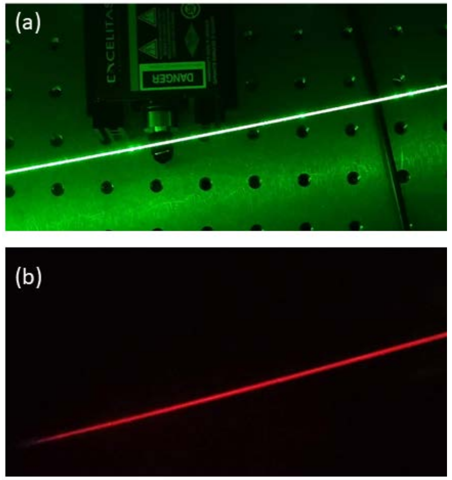
Light intensity distribution for NV red fluorescence



Fluorescence spectrum for:
(a) excitation and detection from the same fibre end
(b) from different ends of the fiber



Light propagation in fibre
(a) Without high pass filter
(b) With the filter



Fibre core:

- Core diameter 50 um
- Schott F2 glass
- Low-index F2 modification for cladding tube
- Measured NA = 0.16

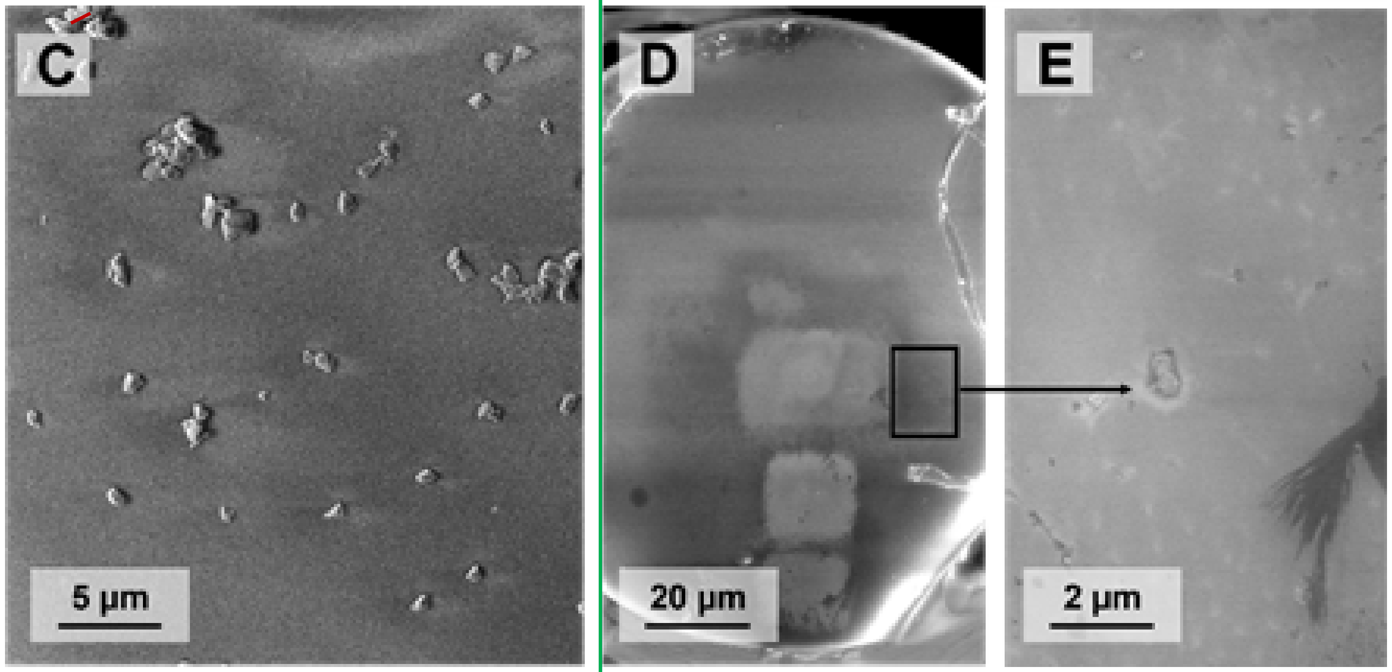
NV^- Zero phonon line at 637 nm visible
Assymetry of spectra
Scattering observed

QUNNA

distribution of diamond particles at the glass surface

Surface of F2 silicate glass preform elements dip-coated with the nanodiamonds
No significant agglomeration
Typical particle-to-particle distance is between 2 µm and 5 µm

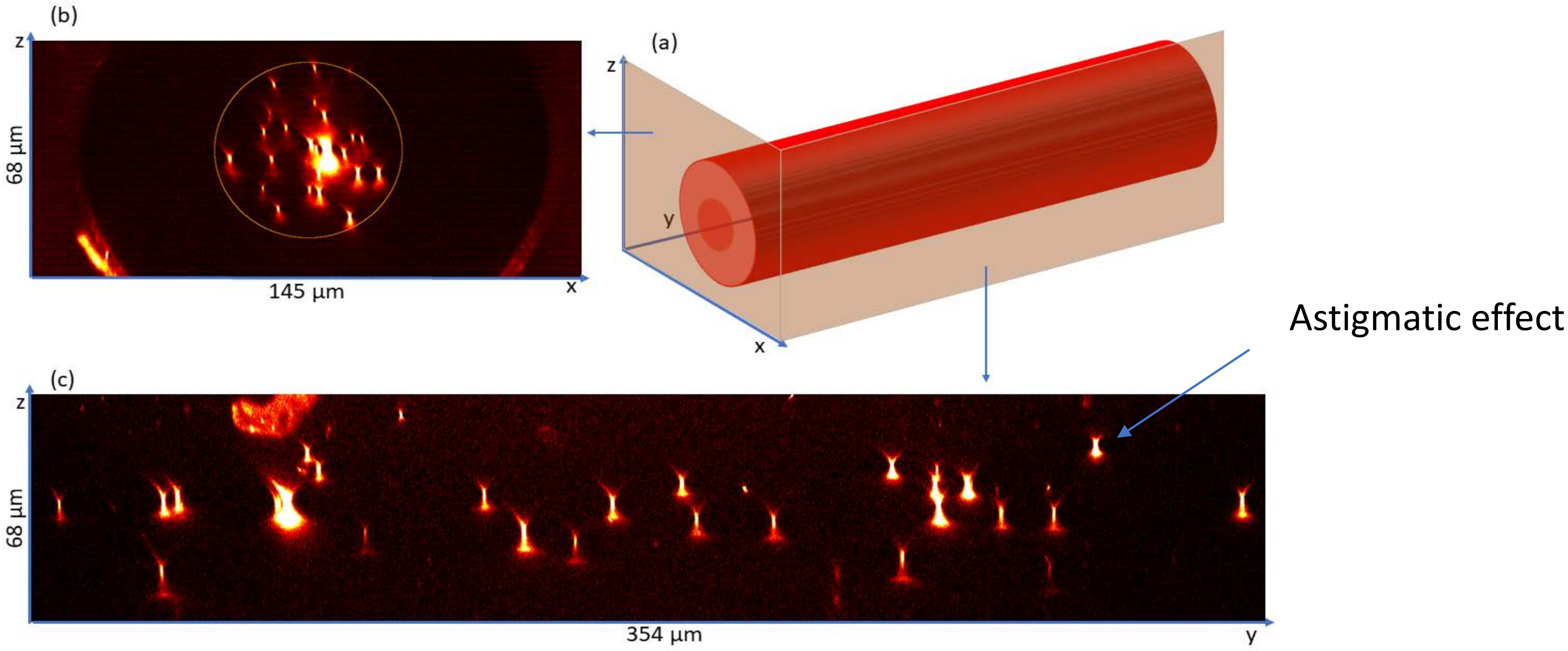
SEM images of fiber cross-section:
- homogenous glass structure with sectionally incorporated diamond particles
- no agglomerates
- no gass bubbles



imaging of diamond particles distributionin the fiber core

Confocal microscopy imaging of ND distribution

- Observable fluorescence of individual NDs



- The method validates a reasonable degree of control over spatial ND distribution
- possible control of ND distribution by layout design

imaging of diamond particles distributionin the fiber core

metodology

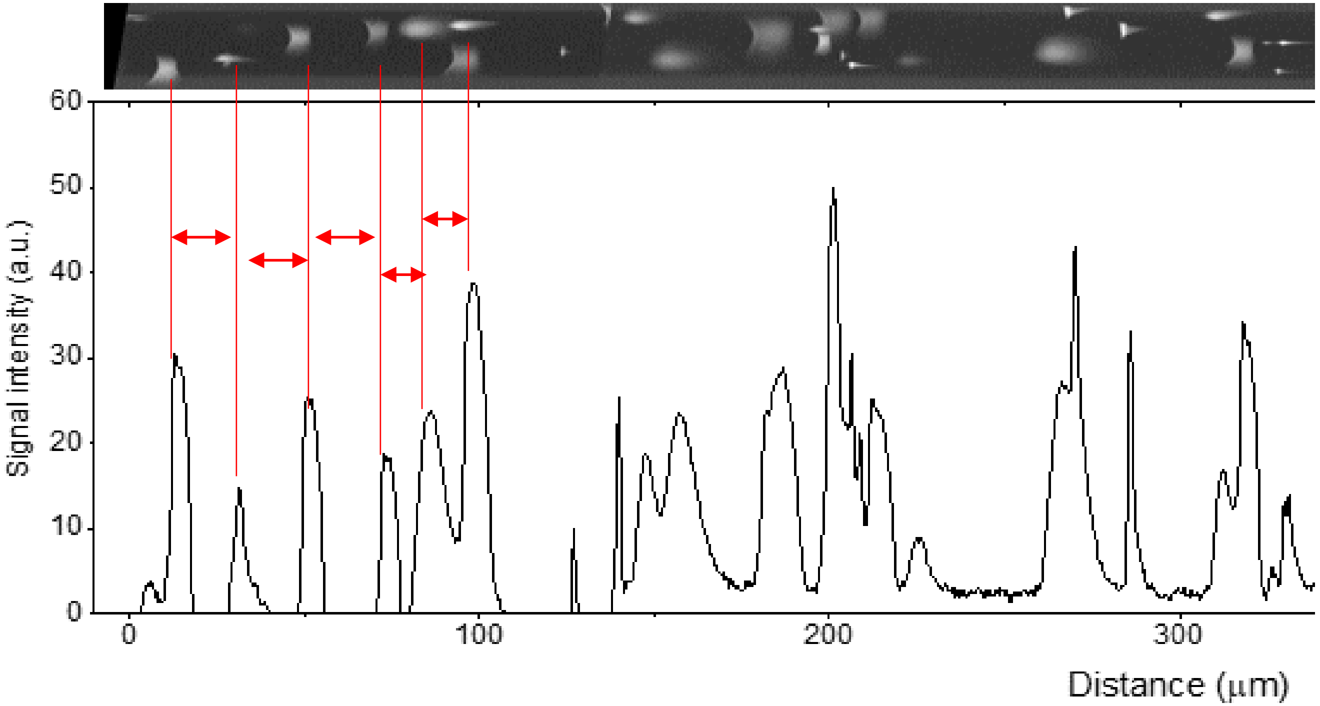
- recording of diamond fluorescence from either the face or the side of a fiber sample under a confocal microscope

- projecting the images from the 3 fiber samples (signal intensity) onto one axis,

- obtaining an intensity curve for either longitudinal or transverse axis of the fiber

- the distance between adjacent peaks is measured and obtained values are stacked in a histogram

Example of fiber image with fluorescing diamonds under a confocal microscope



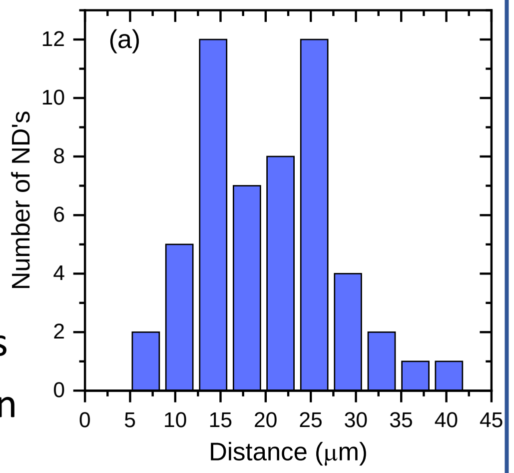
Intensity curve from image projected onto fiber's longitudinal axis

imaging of diamond particles distributionin the fiber core

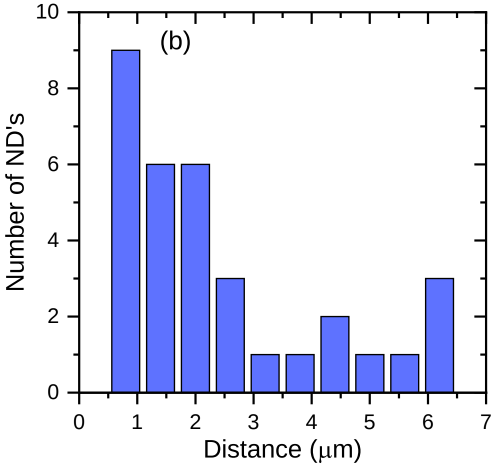
results

Longitudinal separation histogram: major nanodiamond fractions separated either by 15 µm or 25 µm This corresponds to roughly 2.5 µm diamond-diamond distance at recorded at the dip-coated glass surface, when fiber drawing dynamics and drawing thin-down ratio are taken into account.

Longitudinal plane

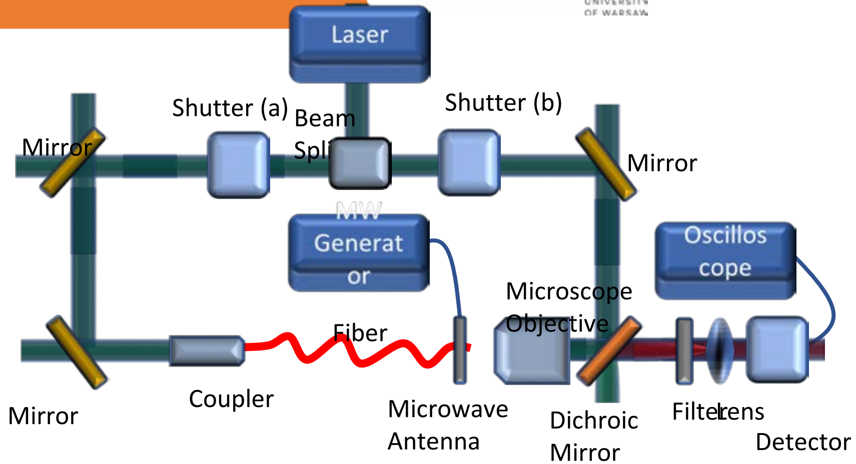


Transverse plane



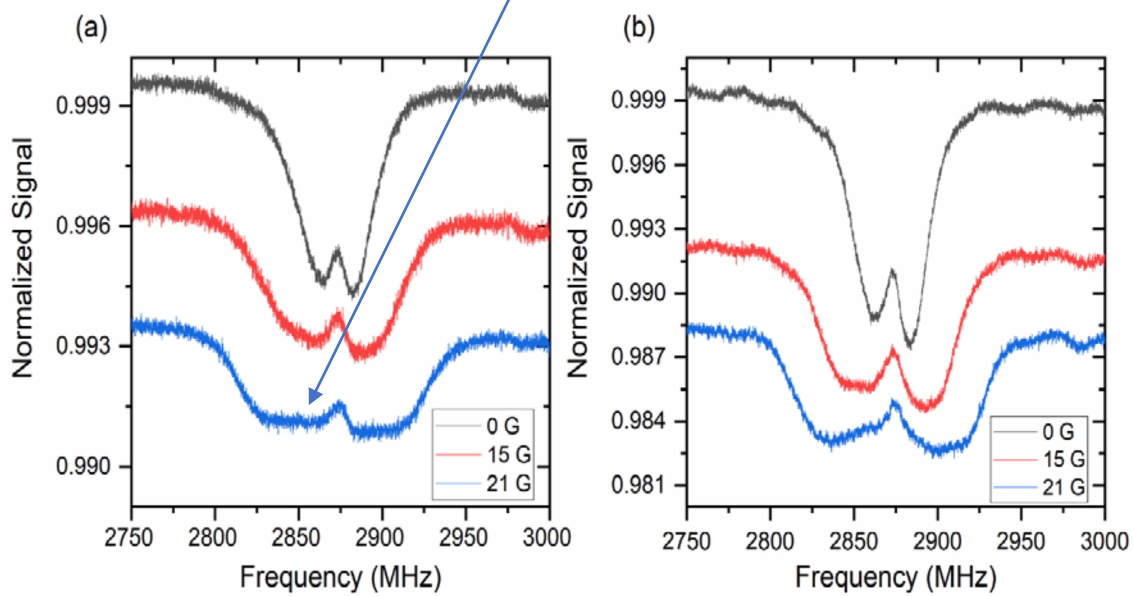
Transverse separation histogram: major fraction of NDs separated 1-3 µm which corresponds with mean cane diameter in the final fiber core (1.5 µm).

Magnetic field sensing performance



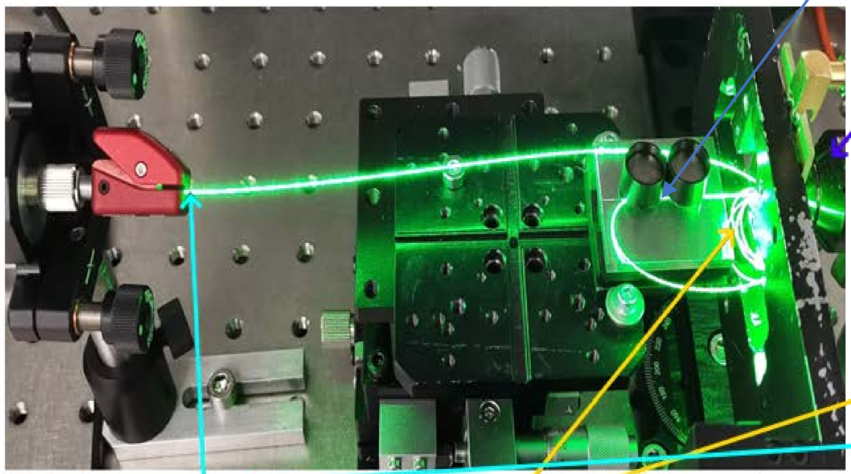
I. Proof of principle experiment: use of optically detected magnetic resonance (ODMR)

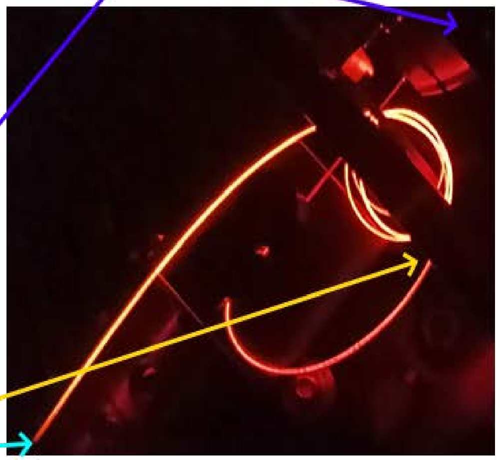
Continuous spectra – randomly oriented NDs



Fiber is looped around microwave antenna

Signal collection





Laser source

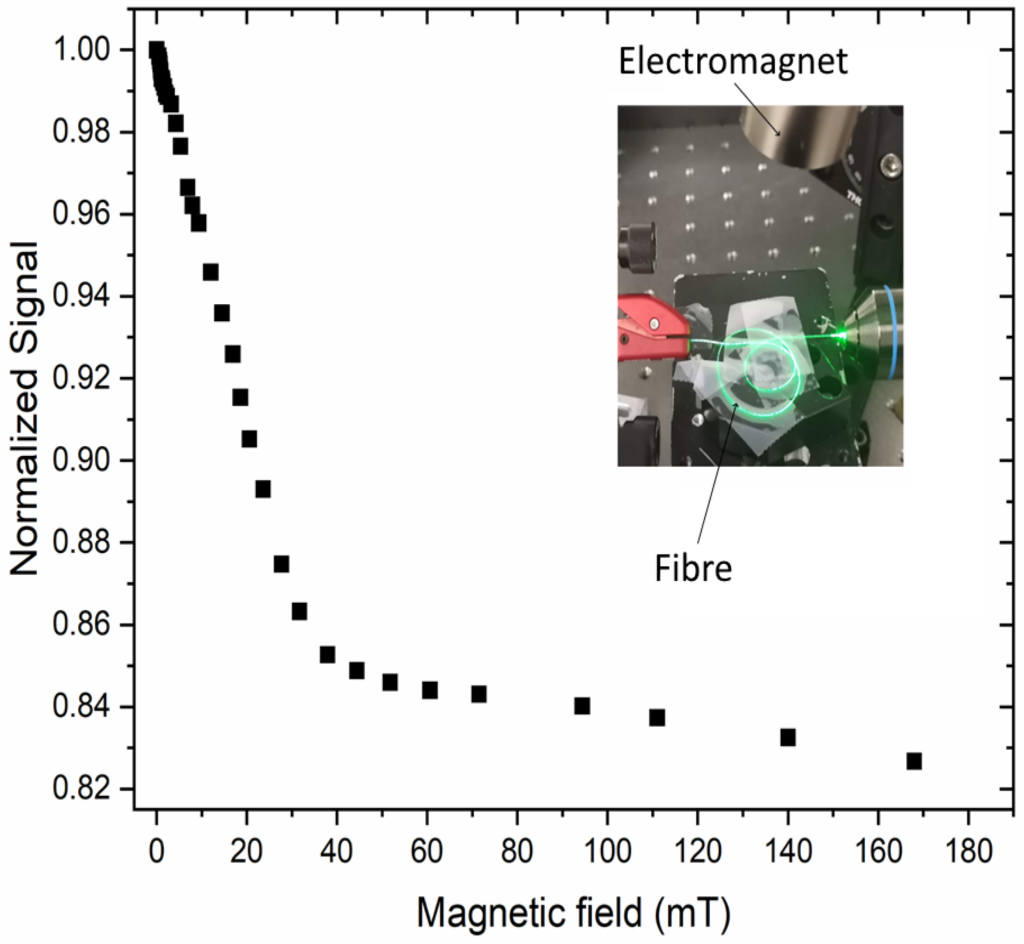
Microwave antenna

- **Optically detected magnetic resonance measurements of fiber spun over a microwave antenna**
- **The read-out contrast between 0.5% to 1.3% - in both cases most of the fiber was not covered by the antenna (related to small fraction of fiber interacting with microwave)**

Magnetic field sensing performance

II. Direct magnetic field measurement - no microwaves

- Typical fluoresecence decay curve observed
- 35 mT dynamics range, but low sensitivity
- (-) No microwaves - requires calibration for readout of magnetic field value
- (++) No microwaves - attractive for biosensing
- Only for high magnetic fields



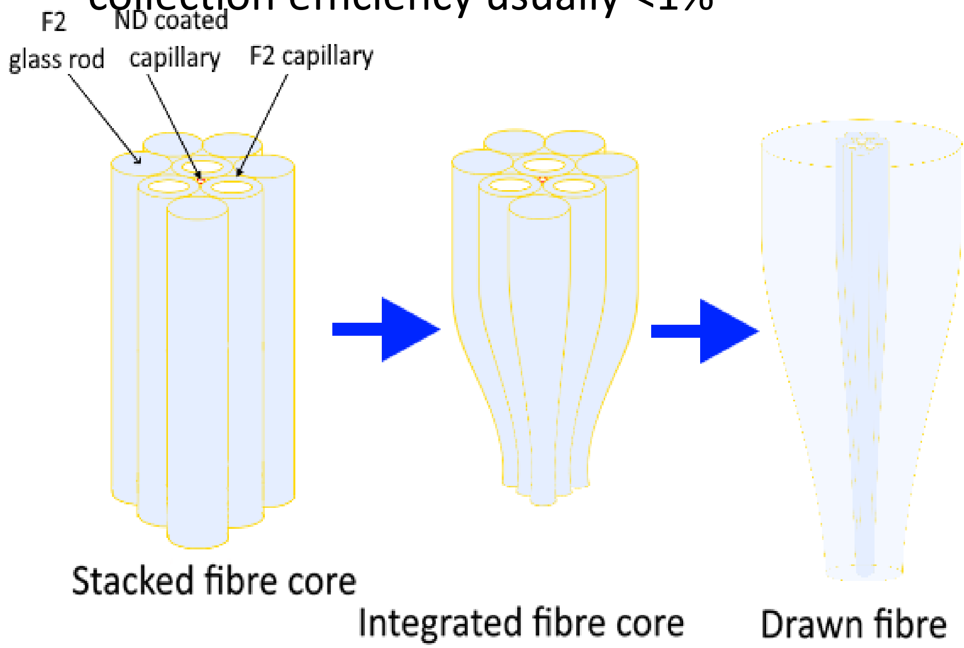
2. The suspended core fiber

State of the art, comparable performance:

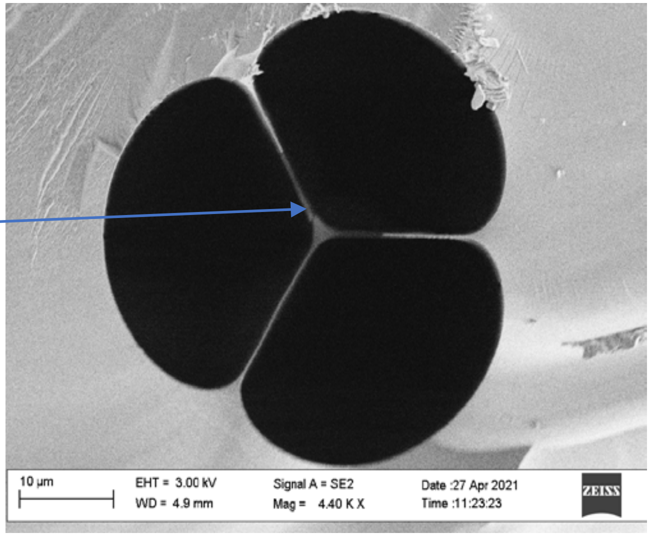
- fiber tip/taper magnetic field probes: tens of µT/sqrt(Hz) magnetic sensitivity & NV fluorescence collection efficiency usually <1%

What we do and why is it imporatant:

- suspended core geometry: ND particles localized inside the volume and along the length of a 1.5µm diam. core
- tight confinement of the guided mode and spatial overlap of NDs with the guided mode



Core diameter 1.5
ND – 750 nm
Individual distribution of ND alnog the fiber



- **The ND suspension introduced inside the glass tube and allowed to dry.**
- **The process repeated 10 times,**
- **avoiding wetting of the tube outside, to ensure even coating of nanodiamonds only at the inside surface of the glass tube**
- **Tube collapsed on fiber drawing tower**

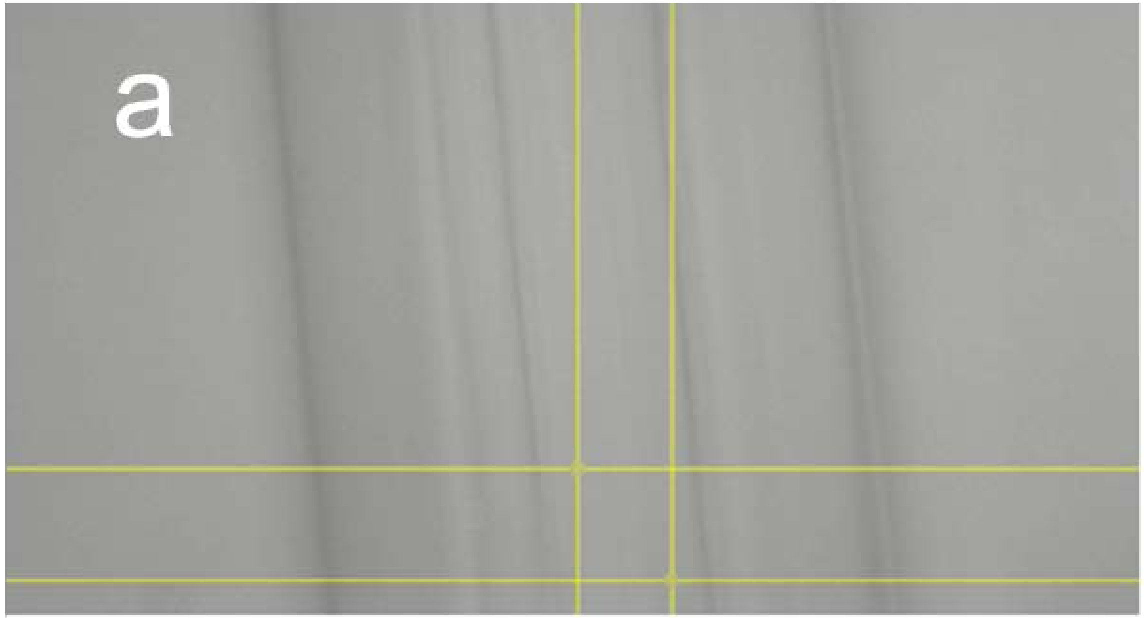
QUNNA

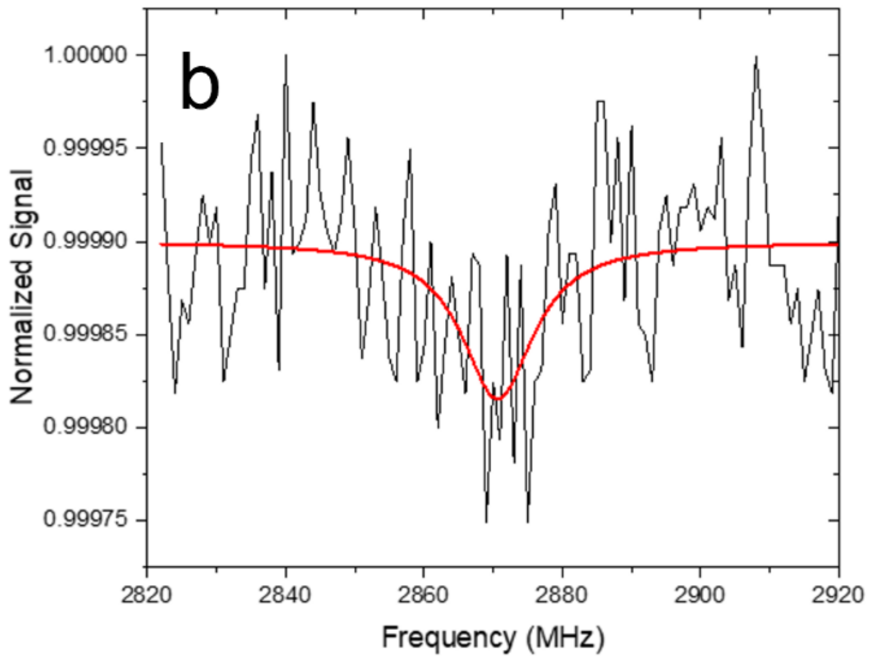
Magnetic field sensing performance

Side-mode operation verification

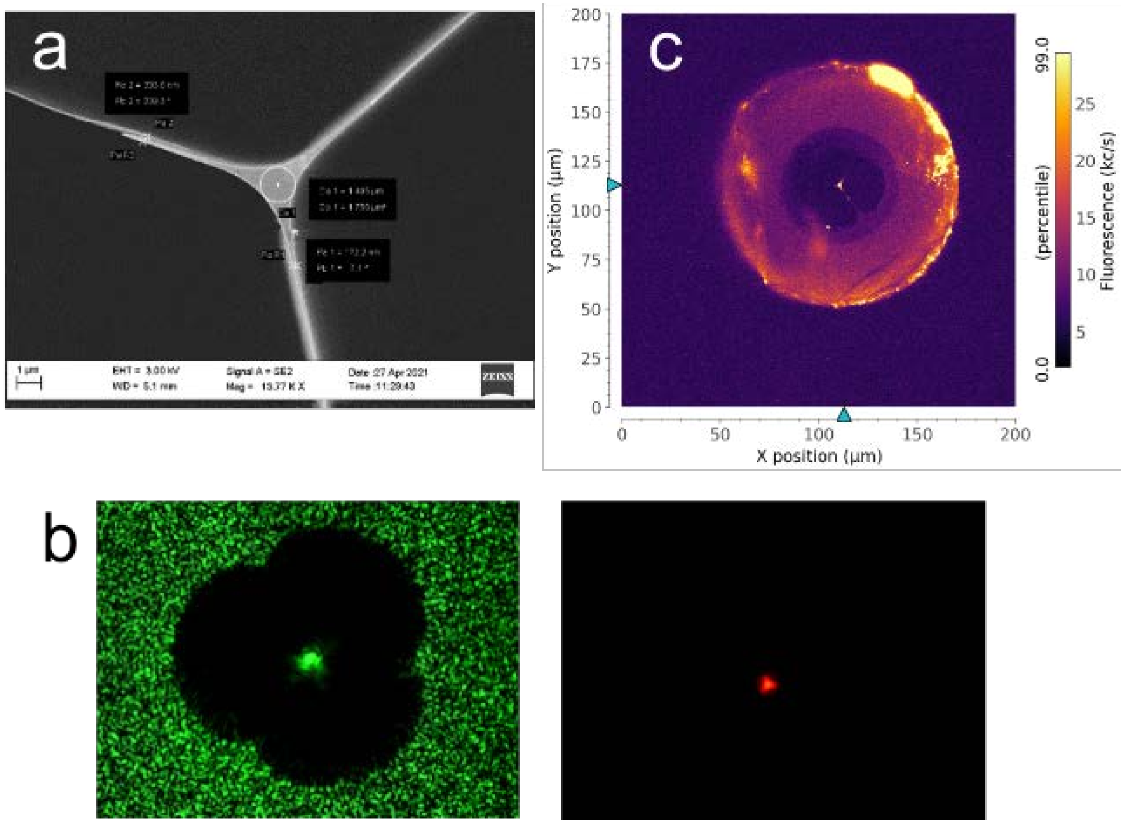
- Attempt to collect NV fluorescence from the fiber
- Hardly any fluorescence visible under the confocal microscope
- Error-bar level sensitivity :-(

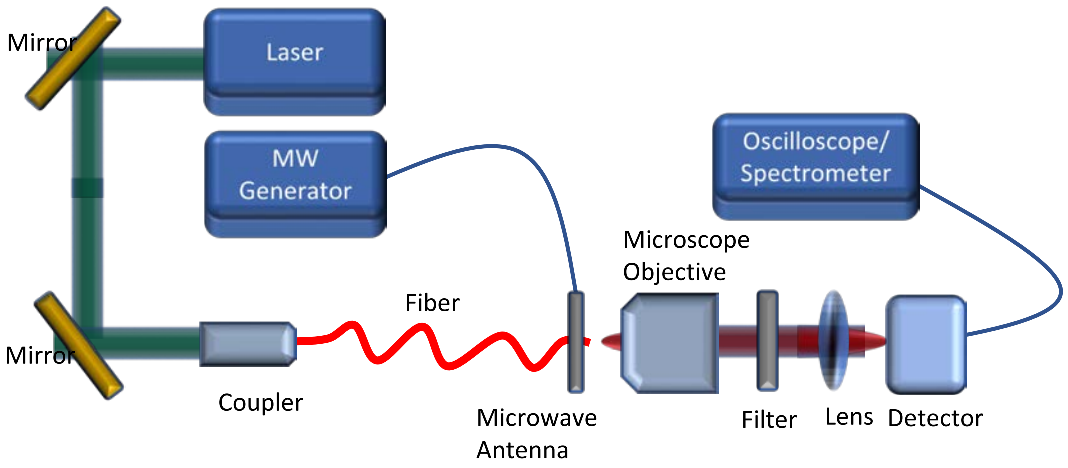
✓ Supports strong confinement and guidance of NV fluorescence

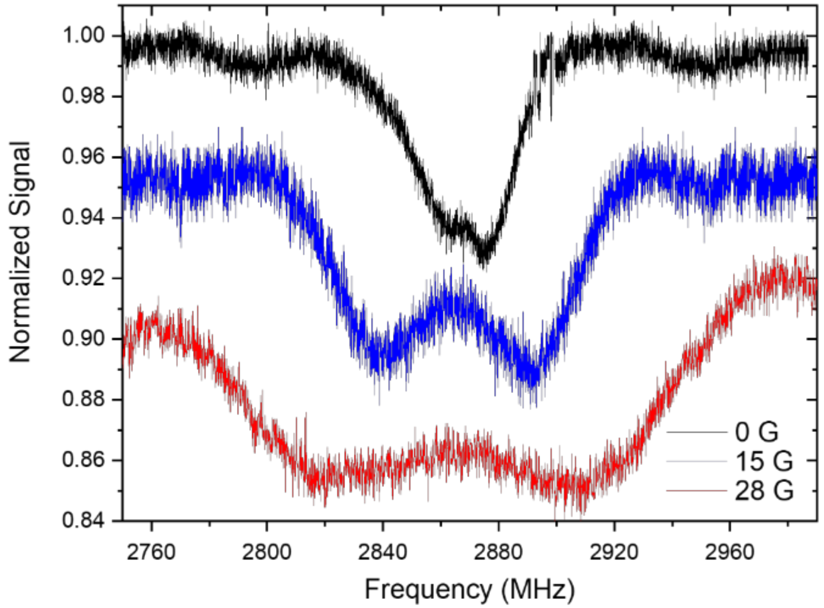




Magnetic field sensing performance



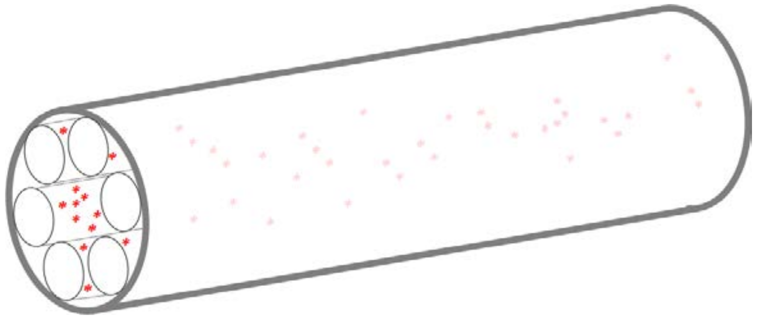




RESULTS:

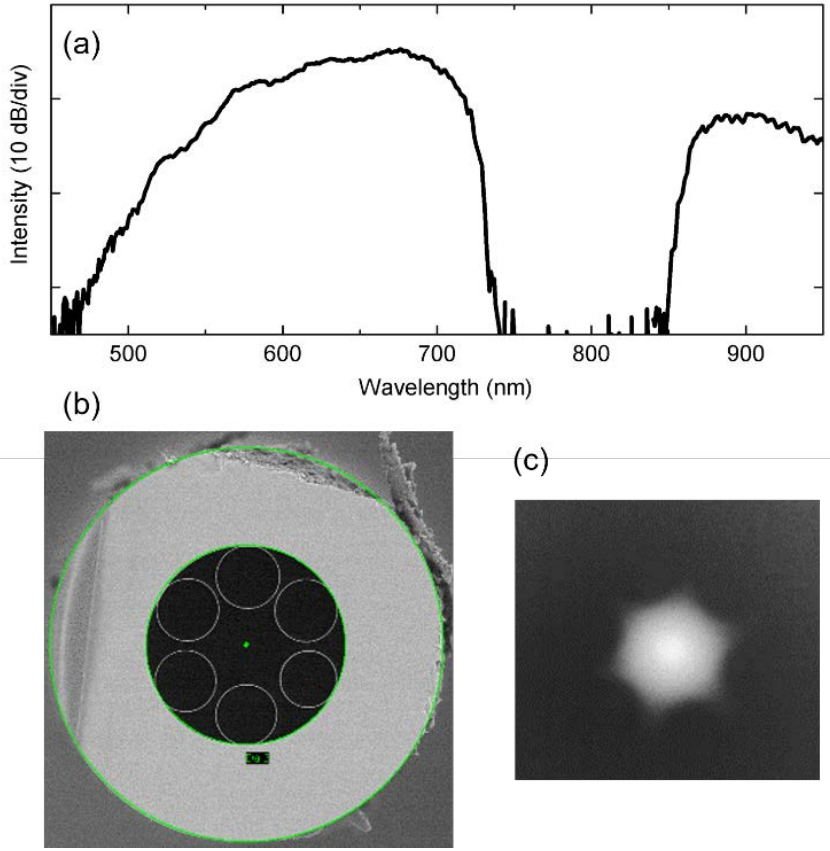
- ✓ Magnetic **sensitivity** 500 nT/sqrt(Hz)
- ✓ suspended core fiber 7% optical readout contrast in end-to-end ODMR
- ✓ („Transmission mode opertation")
- ✓ Strong confinement of NV fluorescence - strong **coupling**

3. Hollow-core anti-resonant fiber



Why hollow core fiber?

✓ Largely unexplored in this application
✓ Coupling to guided mode difficult to anticipate
✓ Possible exposure of NDs to agents introduced into the hollow core
✓ Potentially low scattering loss



Hollow core fiber selection

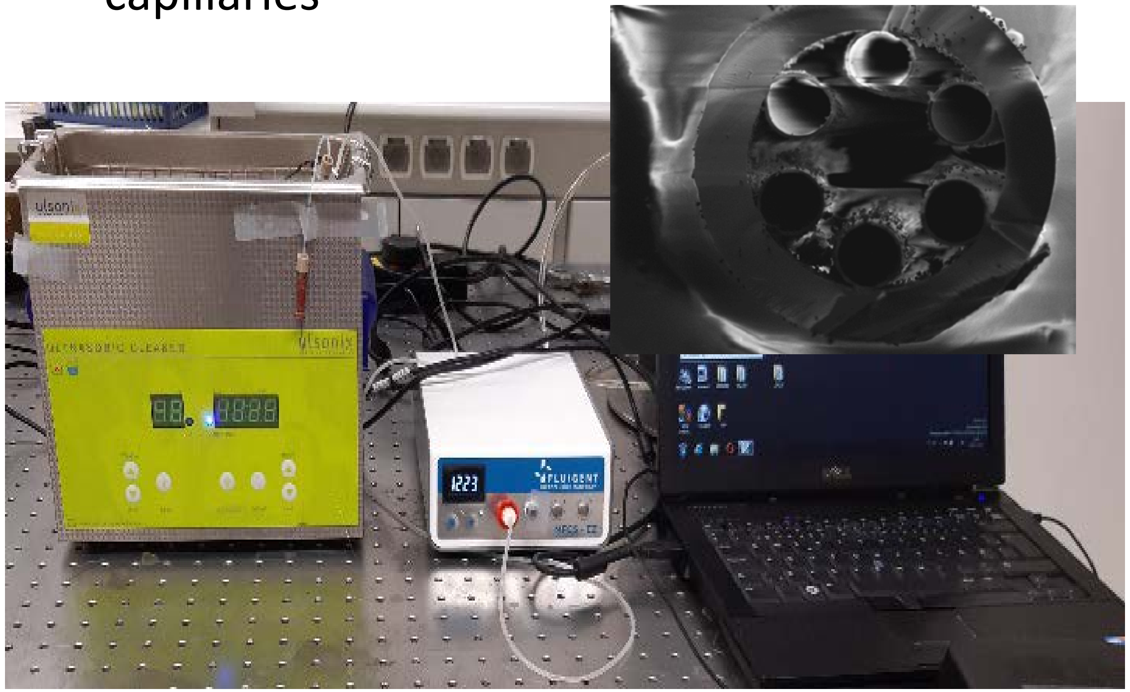
- Silica, six non-touching capillaries in cladding
- 30 µm core diam.
- , 500 nm membrane thickness
- Broad VIS transmission covering both 532 nm excitation line and 637 nm NV^- Zero phonon line
- Effectively single mode at 637 nm

QUNNA

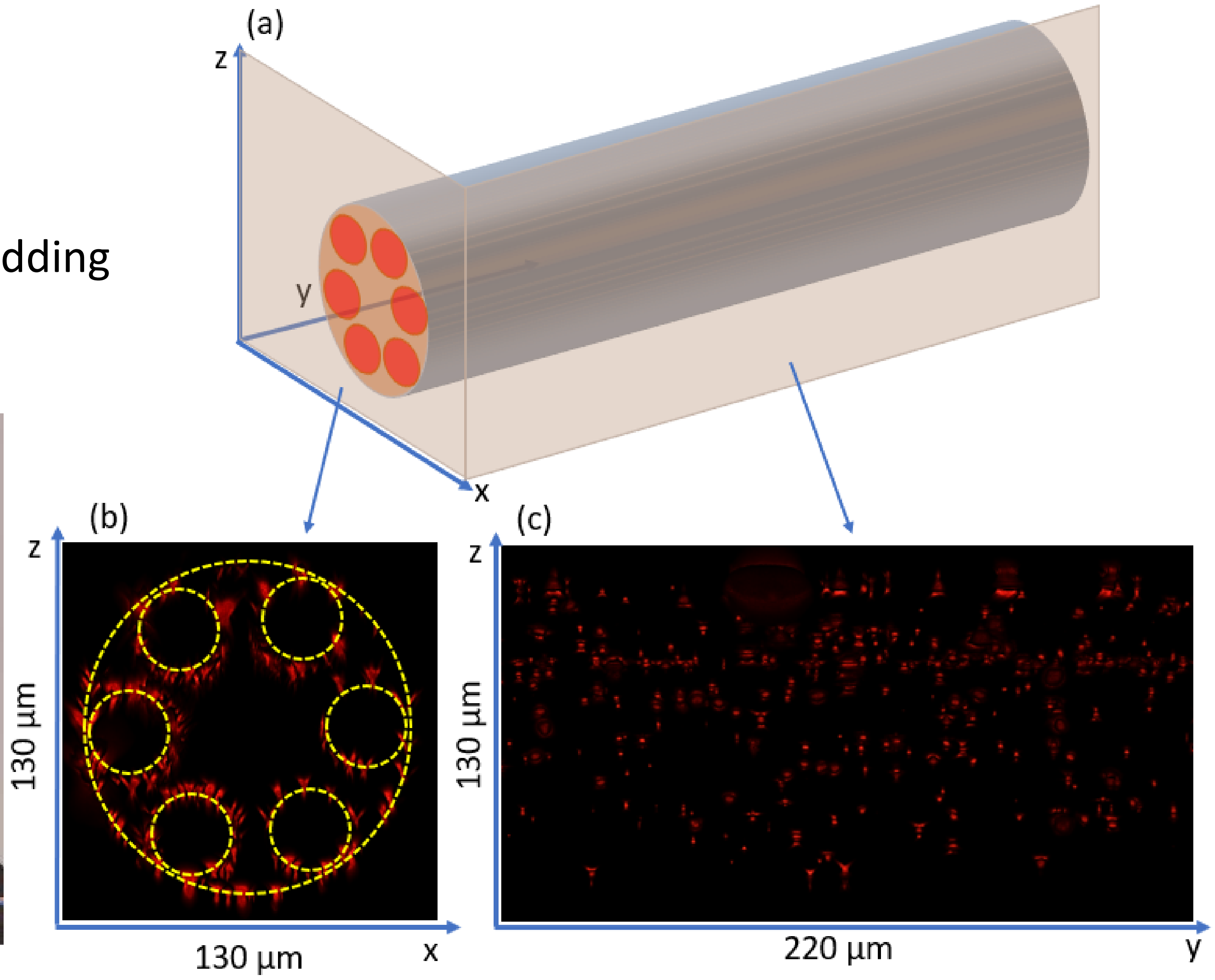
3. Hollow-core anti-resonant fiber

Fiber functionalization and characterization

- 40 cm long fiber samples
- Infiltrated with nanodiamond isopropanol (IPA) suspension by a syringe pump
- Flushed with pristine IPA and dried
- Even longitudinal distribution of particles at caldding capillaries

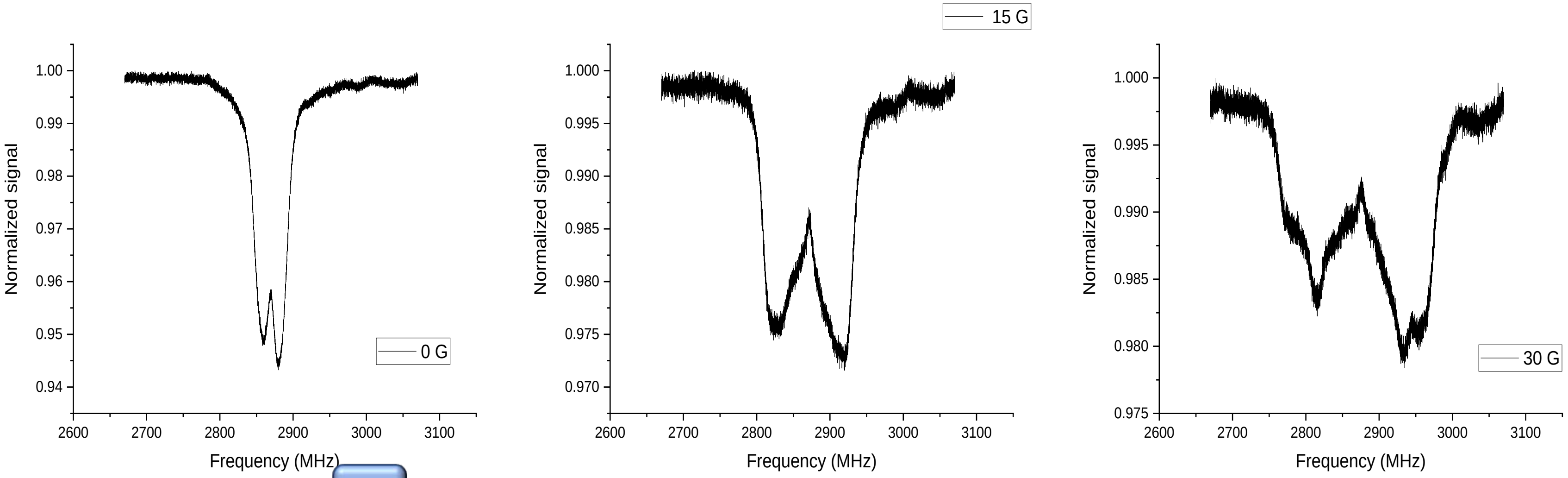


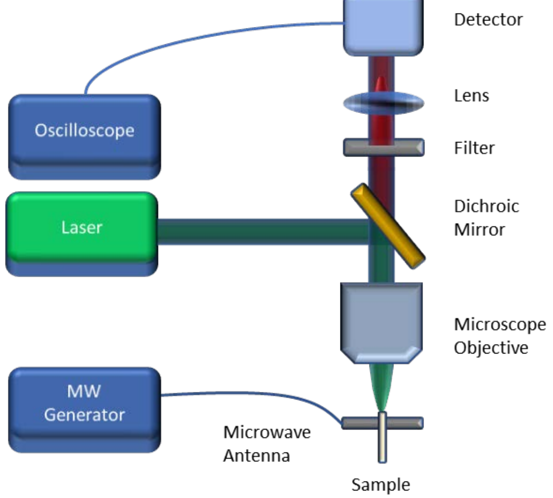
Confocal microscope imaging



3. Hollow-core anti-resonant fiber

Verification of ODMR magnetic field sensing performance





Basic ODMR performance

- 40 cm long fiber samples
- Confirmed guidance of NV^{-} fluorescence in th hollow core
- **Roughly 15%** readout contrast
  in face-to-face readout or side readout
- Moderate 1 µT/sqrt(Hz) sensitivity

Magnetic field gradiometry

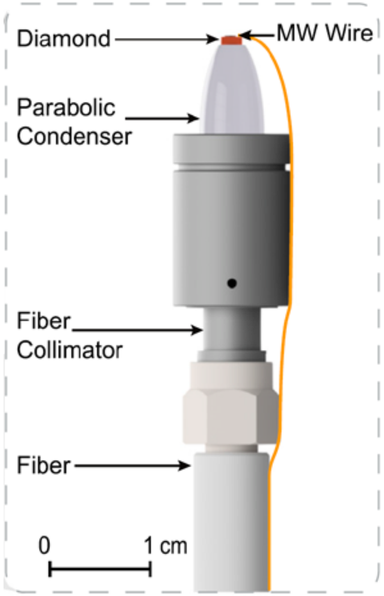
State of the art in NV nanodiamond vector measurements

- Any random oriented nanodiamond fixation precludes a vector measurement

Alternatives already demonstrated:

- Single crystal vector gradiomete have been on fiber tips
- Dual-core fiber gradiometer with random-oriented ND tip

frontiers in Photonics
ORIGINAL RESEARCH
published: 20 August 2021
doi: 10.3389/fphot.2021.732748



Fiberized Diamond-Based Vector Magnetometers

Georgios Chatzidrosos[1,2]*, Joseph Shaji Rebeirro[1,2], Huijie Zheng[1,2]*, Muhib Omar[1,2], Andreas Brenneis[3], Felix M. Stürner[3], Tino Fuchs[3], Thomas Buck[3], Robert Rölver[3], Tim Schneemann[1,2], Peter Blümler[2], Dmitry Budker[1,2,4] and Arne Wickenbrock[1,2]

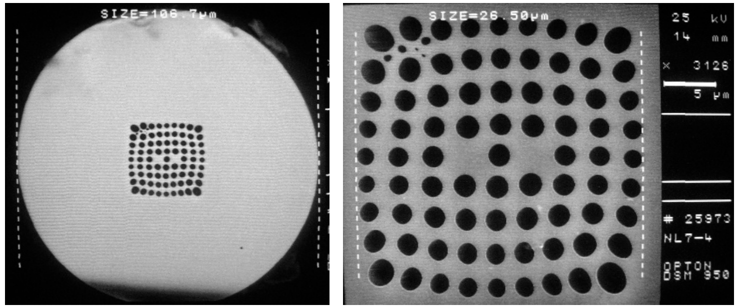
[1]Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, Mainz, Germany, [2]Department of Physics, Johannes Gutenberg-Universität Mainz, Mainz, Germany, [3]Corporate Sector Research and Advance Engineering, Robert Bosch GmbH, Renningen, Germany, [4]Department of Physics, University of California, Berkeley, Berkeley, CA, United States

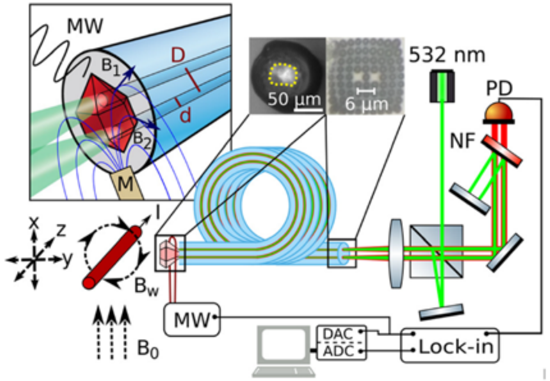
G. Chatzidrosos et al.,
Frontiers in Photonics 2, 732748 (2021)

APPLIED PHYSICS LETTERS 113, 011112 (2018)

Quantum stereomagnetometry with a dual-core photonic-crystal fiber

S. M. Blakley,[1] I. V. Fedotov,[2,3,4] J. Becker,[1] and A. M. Zheltikov[1,2,3,4,5]
[1]Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA
[2]Physics Department, International Laser Center, M. V. Lomonosov Moscow State University, Moscow 119992, Russia
[3]Russian Quantum Center, ul. Novaya 100, Skolkovo, Moscow 143025, Russia
[4]Kazan Quantum Center, A. N. Tupolev Kazan National Research Technical University, Kazan 420126, Russia
[5]Kurchatov Institute National Research Center, Moscow 123098, Russia



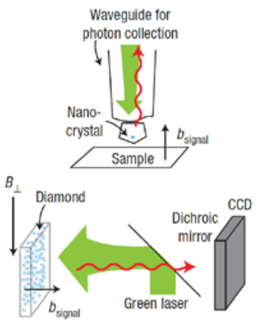


S. M. Blakley et al.,
Appl. Phys. Lett. 113, 011112 (2018)

QUNNA

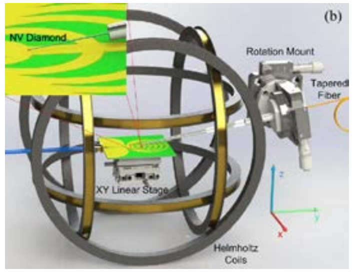
Magnetic field gradiometry - present alternatives employing diamond sensors

Single-crystal diamond-based microscope
Complex but ultra-senstive

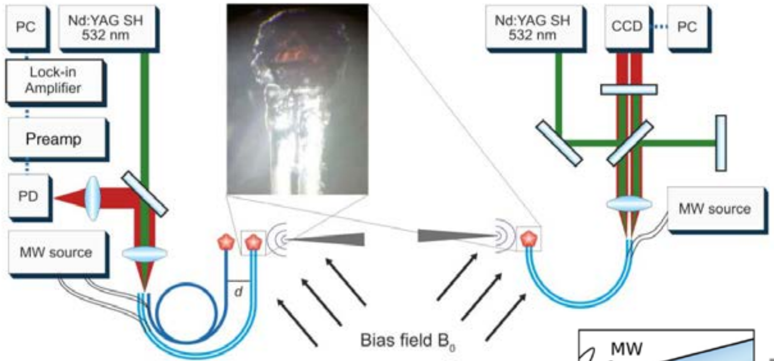


J. M. Taylor et al.,
Nature Physics 4, 810 (2008)

S-C diamond on fiber taper
Robust and sensitive
Requires -preorientation

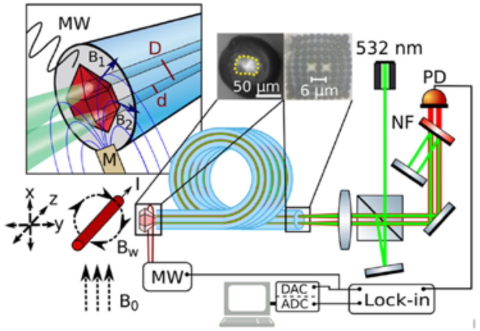


Guo-Bin Chen et al.
IEEE J. Quantum Electron. 56(3), 7500106 (2020)



S. M. Blakley et al.
Opt. Lett. 41(9), 2057 (2016)

Differential gradient measurement
Addressing 1 or 2 diamonds over two separate fibers or 1 diamond over a dual core fiber
- Required pre-oriented diamonds



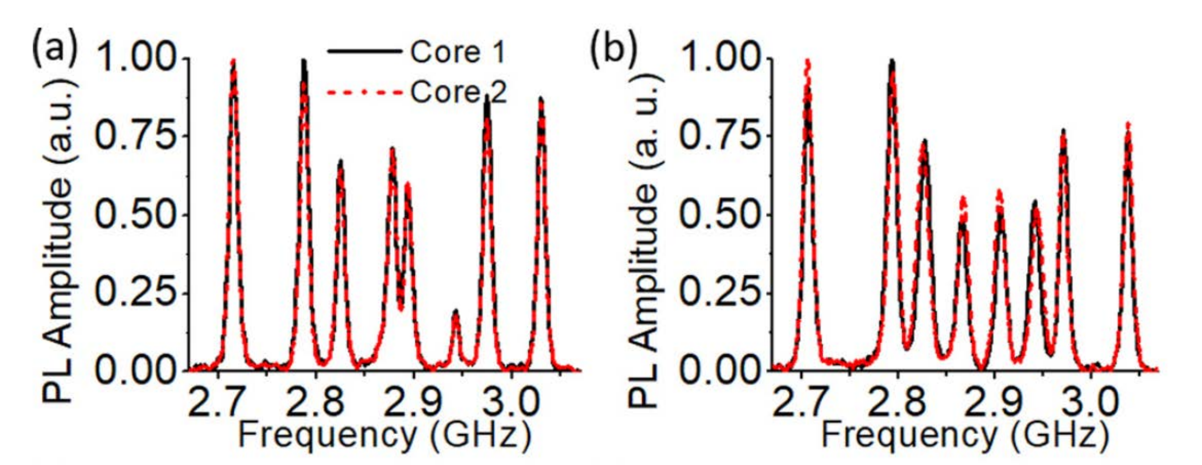
S. M. Blakley et al.
Appl. Phys. Lett. 113, 011112 (2018)

Device simplification

Magnetic field gradiometry - present alternatives employin

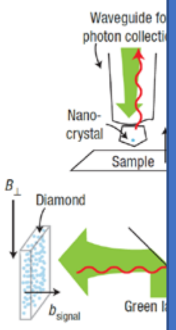
All realizations relied on pre-oriented diamond sensors

for example:



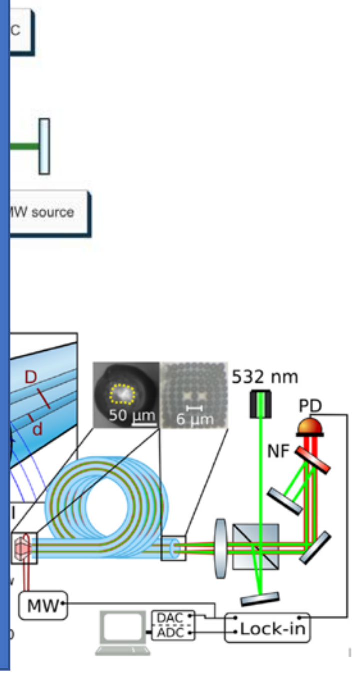
S. M. Blakley et al.
Appl. Phys. Lett. 113, 011112 (2018)

Single-crystal di
microscope
Complex but ult



J. M. Taylor et a
Nature Physics

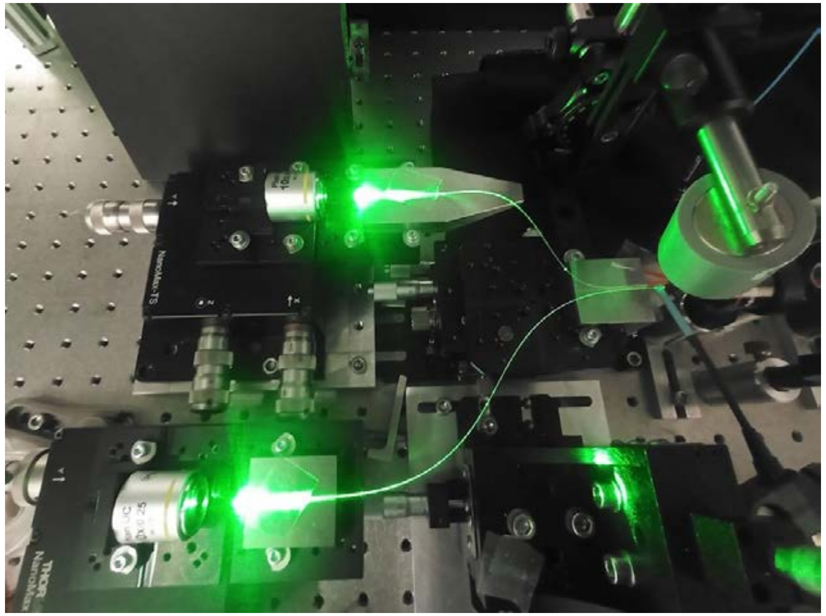
over a dual core fiber
- Required pre-oriented diamonds

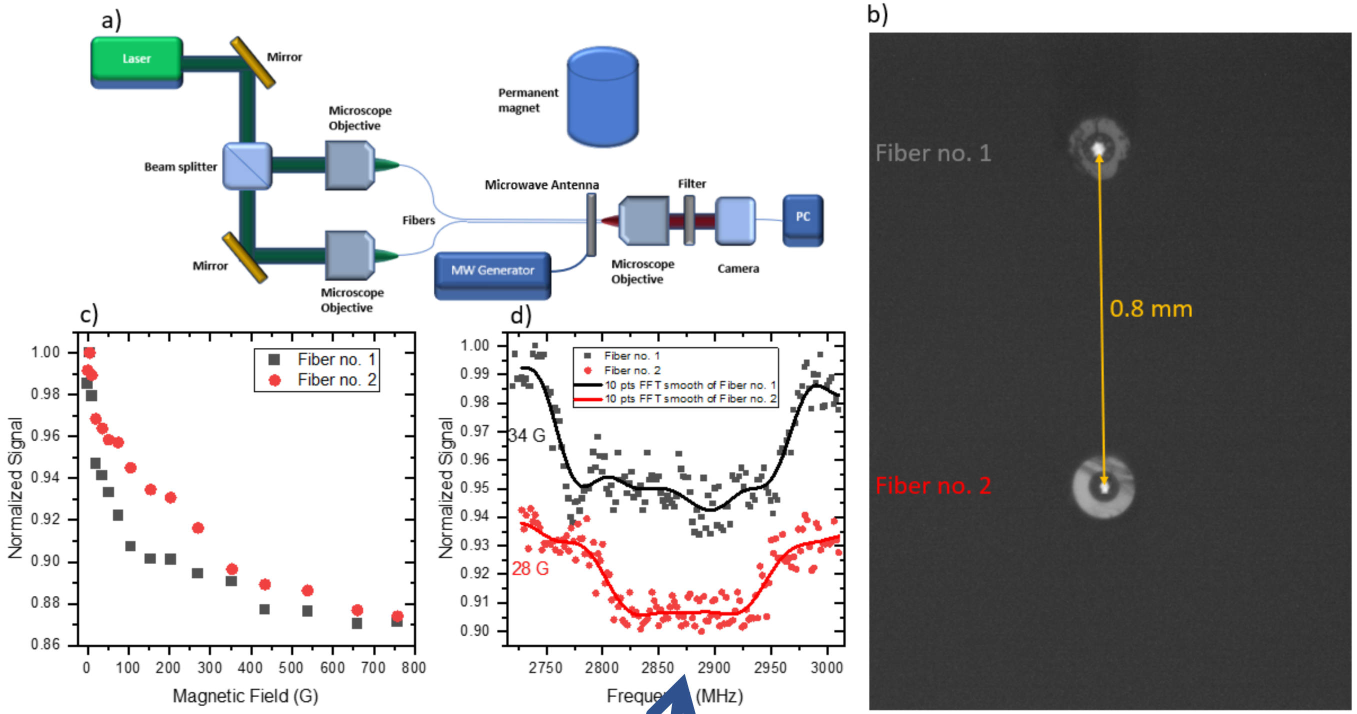


S. M. Blakley et al.
Appl. Phys. Lett. 113, 011112 (2018)

Device simplification

NV⁻ nanodiamond hollow core fiber proof-of-concept gradiometer





Experimental setup

- Two 40 cm long hollow core fibers with NV⁻ nanodiamonds
- Fiber outputs positions one under-the-other under a magnet
- Removable microwave antenna in place

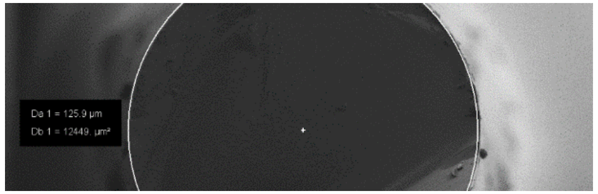
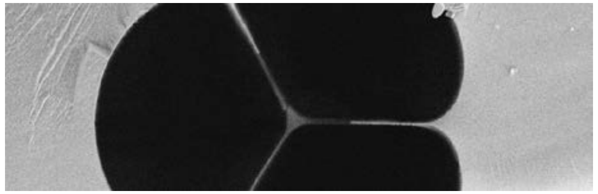
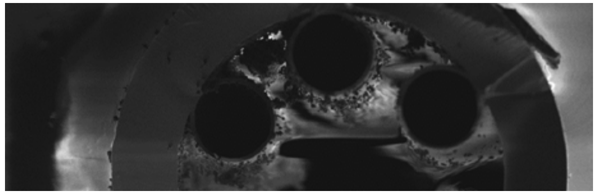
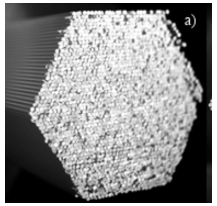
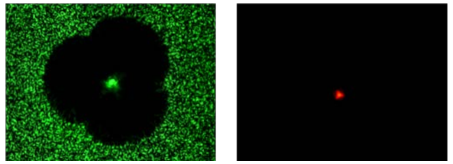
No microwaves variant **ODMR variant**

- Two experiments
- No-MW variant intresting for bio but requires calibration
- ODMR variant with 5% relative readout contrast (out of 15% achievable single-fiber ODMR contrast)

Magnetic field gradient obtained despite entirely random diamond orientation

QUNNA

Performance comparison

	Step-index multimode fiber	Suspended core fiber	Hollow-core fiber
			
Material	soft glass (F2)	soft glass (F2)	fused silica
	MDNV1um, Adámas Nanotechnologies, in all fibers		
ODMR readout contrast Direct B-field meas.	3% yes	7% no	15% yes
Sensitivity	5 µT/$\sqrt{Hz}$	500 nT/$\sqrt{Hz}$	1 µT/$\sqrt{Hz}$
Usefull fiber length and limitating factor	25 cm scattering	20 cm scattering	40-50 cm infiltration uniformity
Main advantages	Transverse nanostructure shaping  A. Filipkowski et al. Carbon (2022)	Strong confinement and guiding  A. Filipkowski et al. Opt. Express (2022)	controlled exposure of nanodiamonds strong NV$^-$ signal, low propagation loss

Optical sytems not optimised – still room for improvment

II. Optical fibers with nanodiamonds: reduction of nonlinearity

Nonlinear refractive index

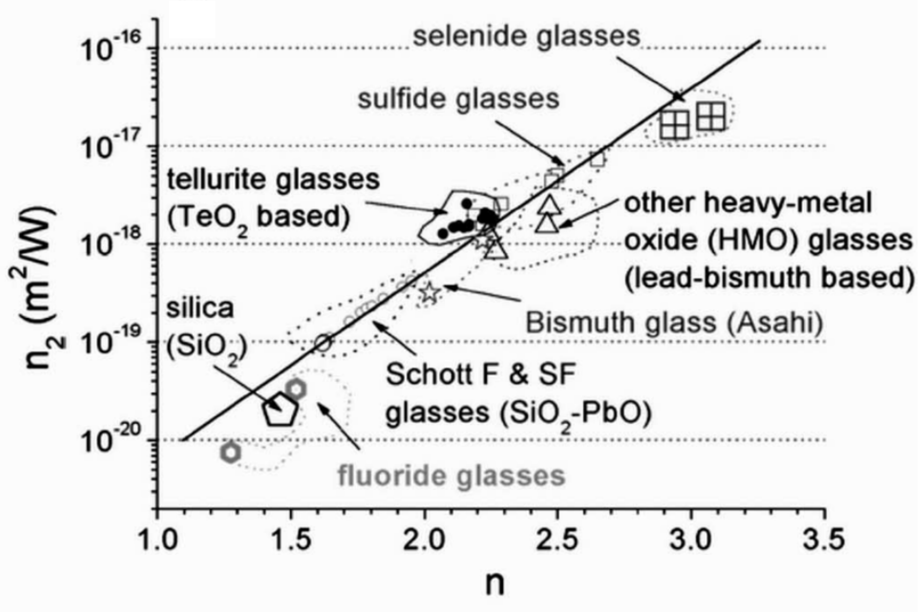
Nonlinearity

material: $n = n_0 + n_2 I_0$

optical fiber: $\gamma = \frac{2\pi n_2}{A_{eff}\lambda}$ [1/(W·km)]

$$n_2 = \frac{3}{4}\frac{\chi^{(3)}}{c\varepsilon_0 n_0^2} \quad [\mathrm{m^2/W}]$$

- electronic response + thermal effects
- nonlinear index of refraction n_2 in the range of 10^{-20} (fused silica, ZBLAN) up to 10^{-17} m^2/W (chalcogenide glass)



X. Feng et. al., *J. Lightwave Technol.* **23**, 2046, (2005).

Negative index of n_2:

- semiconductors (e.g. GaAs, AlGaAs), strong wavelength dependence, high negative n_2 near to energy gap
- organic liquids
- nanoparticles (Au, Ag, diamond), environment-surface effects

Motivation

nonlinear index of refraction n_2

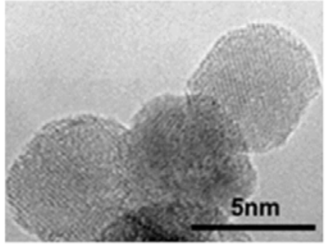
crystalline diamond

$n_2 = + 4 \div 16 \times 10^{-20}\ m^2/W$ [1]

nanodiamonds

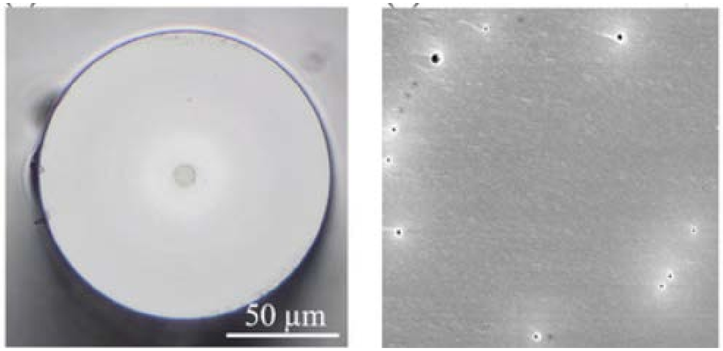
$n_2 = - 2 \times 10^{-17}\ m^2/W$ [2]
(nanocrystalline membrane, 1 µm)

$n_2 = - 6 \times 10^{-19}\ m^2/W$ [3]
(detonation nanodiamond, 5-10 nm)



- **nanodiamonds:**
  - negative n_2
  - size of particles and surface functionalization -> modification of n_2
  - successful integration with soft glass (eg. Schott F2) [4]

- **GOAL: fiber-drawable hybrid glass with reduced n_2**
- NDs influence on the nonlinearity of hybrid material
- in perspective, fiber optics with zero nonlinearity



Ref [4]

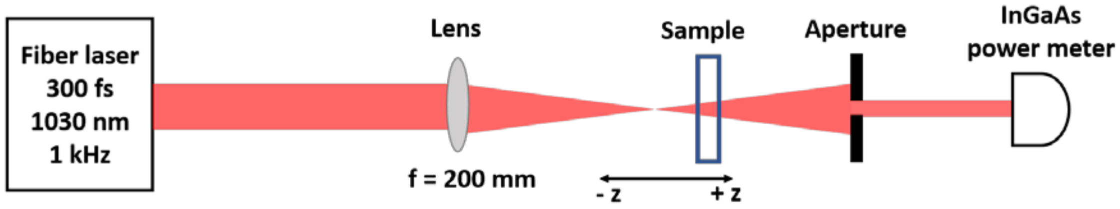
[1] J.M.P. Almeida et. al., „Nonlinear optical spectrum of diamond at femtosecond regime", *Sci. Rep.* **7**, 2017
[2] F. Trojánek et. al., „Nonlinear optical properties of nanocrystalline diamond", *Opt. Express* **18**(2), 2010
[3] O. Muller et. al., „Optical limiting properties of surface functionalized nanodiamonds probed by the Z-scan method", *Sci. Rep.* **9**, 2019
[4] D. Bai et al., „Fluorescent diamond microparticle doped glass fiber for magnetic field sensing," *APL Materials* 8, 081102 (2020)

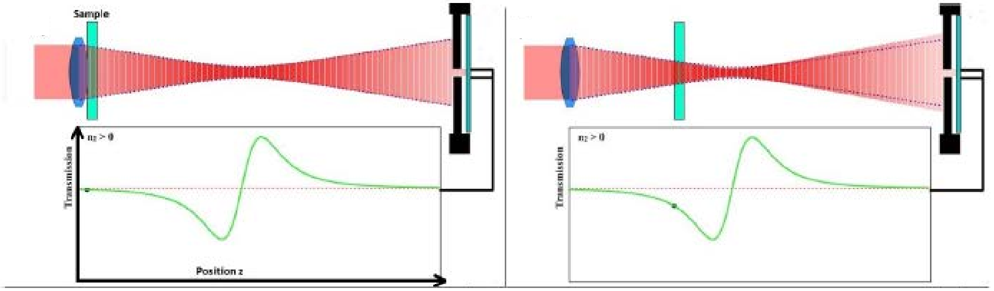
Measuring method – Z-scan

- nonlinear phase change at the beam waist (sefl-focusing $n_2 > 0$, self-defocusing $n_2 < 0$)

$$\Delta\phi = \frac{2\pi}{\lambda} n_2 I_0 L_{eff} \qquad I_0 = \frac{2P_0}{\pi\omega_0^2} \qquad L_{eff} = \frac{(1 - e^{\alpha L})}{\alpha}$$

L - sample thickness
α - linear absorption coefficient
ω_0 - beam waist at the focus (radius)
P_0 - peak power

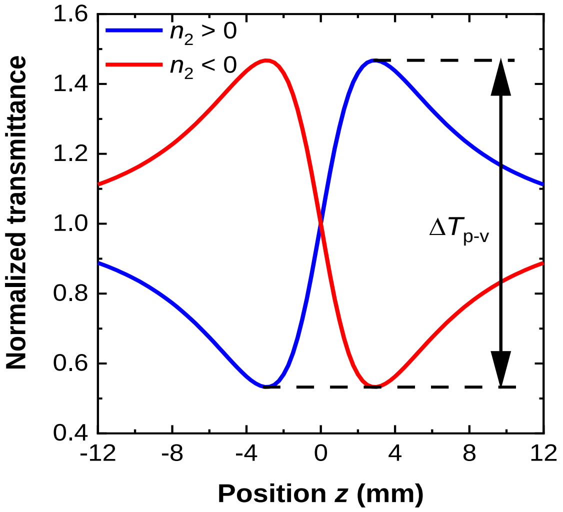




- normalized transmittance (closed aperture)

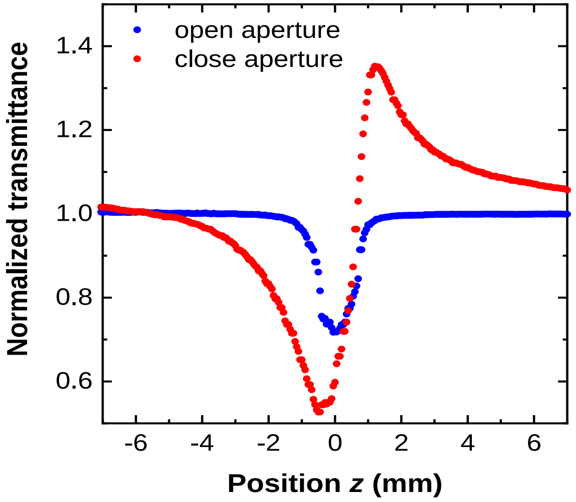
$$T(z, \Delta\Phi_0) = 1 - \frac{4x\Delta\Phi_0}{(x^2+1)(x^2+9)} \qquad x = z/z_0$$

z_0 - Rayleigh range



- closed aperture ➡ nonlinear refraction n_2
- open aperture ➡ nonlinear absorption β

M. Sheik-Bahae et. al. , “Sensitive measurement of optical nonlinearities using a single beam,” *IEEE J. Quantum Electron.* **26** (4), 760-769 (1990)



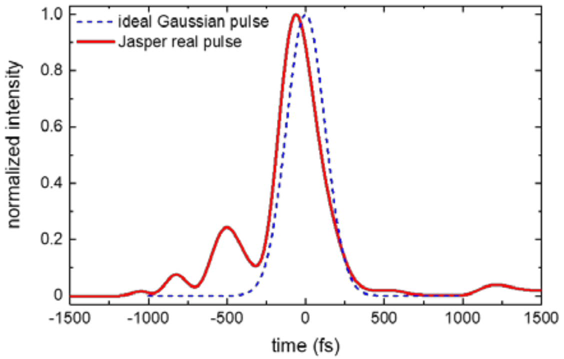
Z-scan, system parameters

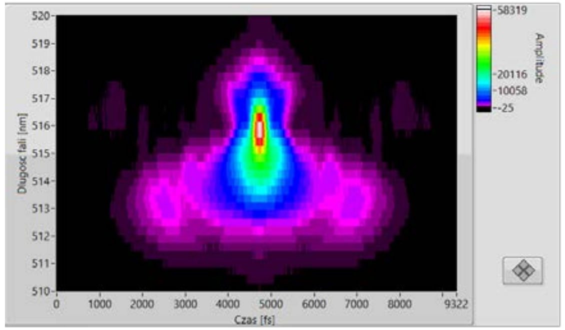
- laser pulse characterization (Frequency Resolved Optical Gating - FROG)

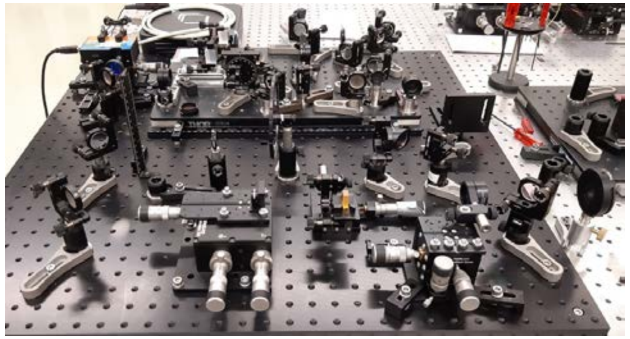
Fluence Jasper X0
(1030 nm, 300 fs, 1 kHz)

peak power scaling factor

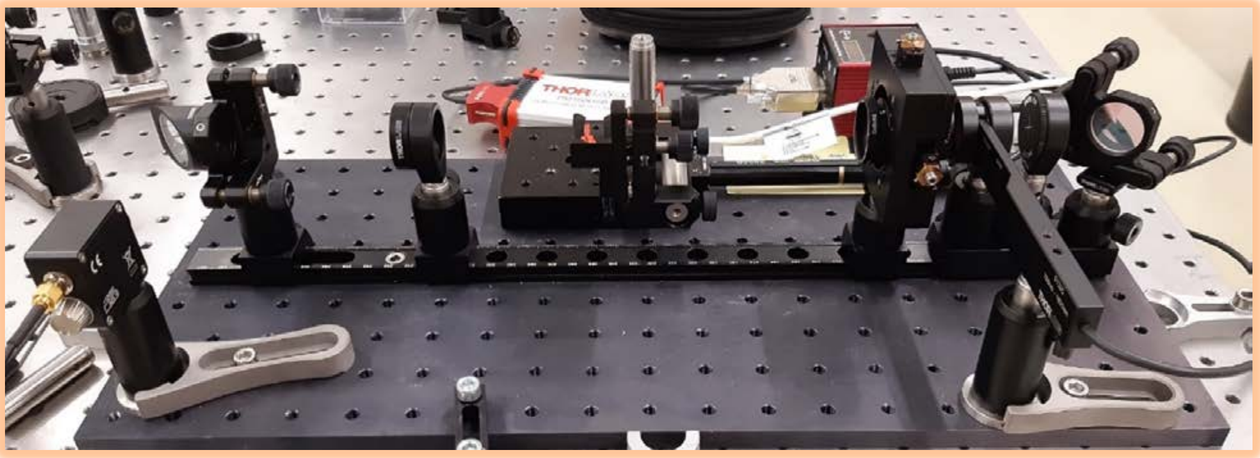
$$\frac{P_{real}}{P_{Gauss}} \approx \mathbf{0.8}$$







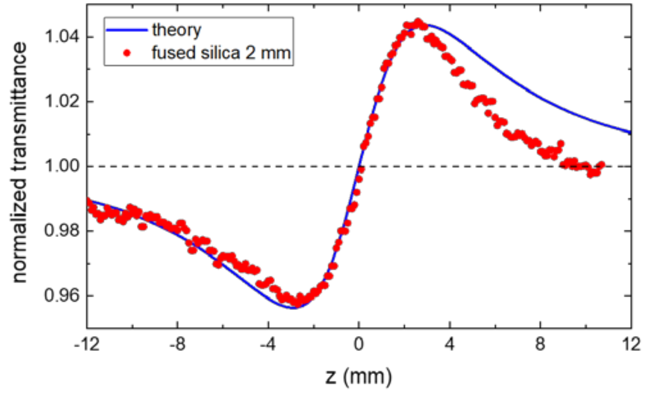
- portable Z-scan setup



- plano-convex lens *f* = 200 mm
- beam parameters: $M^2 < 1.2$, $\omega_0 = 37\ \mu m$, $z_0 = 4.2$ mm
- beam diameter at scanning boundaries: 230 µm
- low power measurement for liquids ($P_{avg} = 2.27$ mW, $E_p = 2.2\ \mu J$, $I_0 = 240\ GW/cm^2$)
- travel range 24 mm
- InGaAs power meter (700 ÷ 1800 nm)

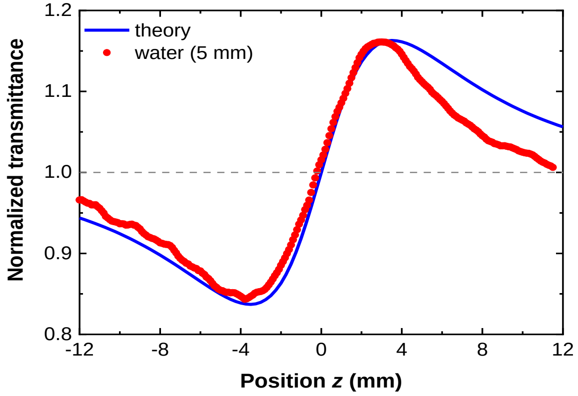
System check

- reference fused silica sample (2 mm)



2.1 – 2.3 x 10^{-20} m^2/W

- distilled water in quartz cuvette (5 mm)



3.27 x 10^{-20} m^2/W

Ref. [1], for 300 fs
3.35 x 10^{-20} m^2/W

- toluene in quartz cuvette (5 mm) **17 x 10^{-20} m^2/W**

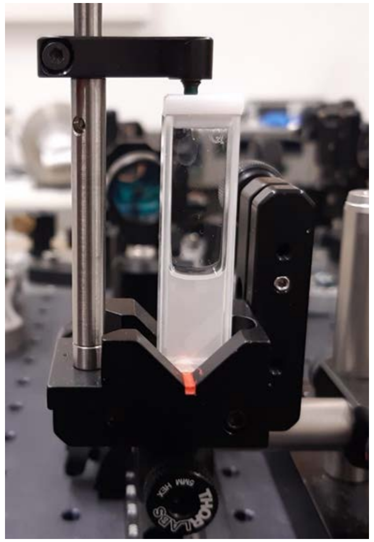
- results for reference samples (thin and thick sample assumption)

sample	sample thickness	lens	n_2	n_2 [Ref]
Fused silica	2 mm	50 mm (Z_0 = 0.86 mm)	**1.8** – thin sample **2.1** – thick sample	2.24 (1.7 – 2.7)
	2 mm	100 mm (Z_0 = 3.44 mm)	**2.1** – thin sample **2.2** – thick sample	
	5 mm	100 mm (Z_0 = 3.44 mm)	**2.2** – thin sample **2.1** – thick sample	
Schott F2	2 mm	50 mm (Z_0 = 0.86 mm)	**5.0** – thin sample **5.7** – thick sample	2.9 8.9
	2 mm	100 mm (Z_0 = 3.44 mm)	**6.9** – thin sample **7.0** – thick sample	
YVO4	0.9 mm	50 mm (Z_0 = 0.86 mm)	**18.6** (pol1), **18.3** (pol2)	15 - 19

n_2 x 10^{-20} m^2/W

[1] M. L. Miguez et. al., "Measurement of third-order nonlinearities in selected solvents as a function of the pulse width," *Opt. Express* **25**, 3553-3565 (2017)

Nanodiamond in water



- Why water?

  low n_2 and dense enough to avoid settling down
  isopropanol? Quick particles settling -> unrepeatable scans
  DMSO? Very stable suspension but high n_2 (NDs don't change n_2 of suspension)

- samples:
  1. detonation nanodiamonds (DND; Adámas Nanotechnologies, dominant particles size 5-10 nm), concentration of **0.01 mg/ml**
  2. DND concentration of **0.1 mg/ml**
  3. monocrystalline synthetic nanodiamonds (MSY, Pureon, average size 250 nm), concentration of **0.01 mg/ml**

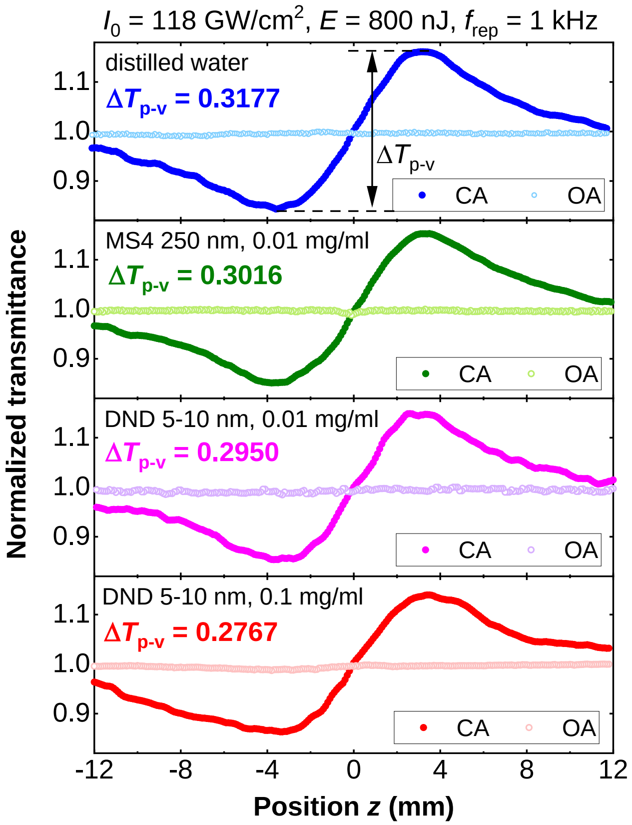
- preparation:
  1. mechanical shaking + 1h in ultrasonic cleaner
  2. measurement in quartz cuvette (1 mm wall thickness and 5 mm optical path)

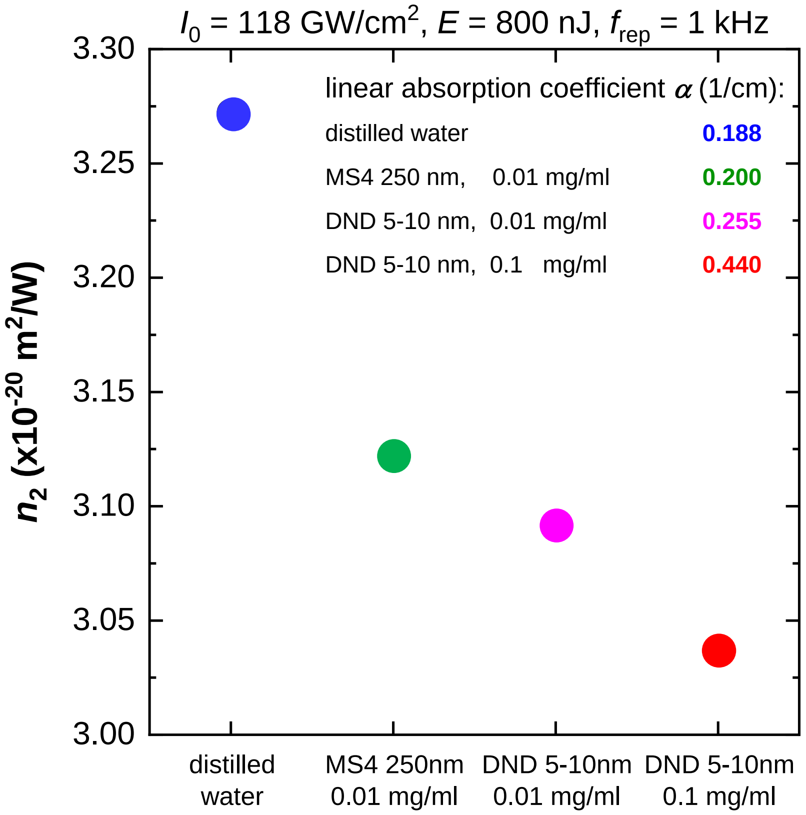
- absorption coefficient α
  reflection from 4 surfaces included

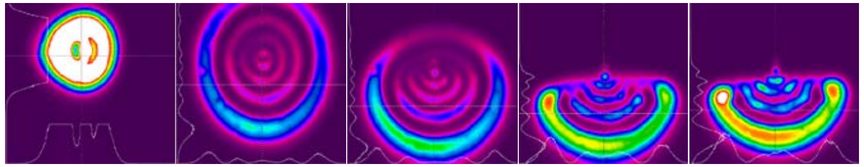
$$\alpha = -\frac{1}{L}\ln\left(\frac{P_{out}}{P_{in}(T_1T_2)^2}\right)$$

Nanodiamond in water

- requirements for the selective measurement of electronic response in liquids: **short pulses (< ps) and low repetition rate (< 1 kHz)**
- long pulses or high repetition rate -> **thermal lensing** -> (spatial self-phase modulation)







- α rises for higher concentration of NDs -> scattering
- small particles -> lower n_2
- high concentration -> lower n_2
- distilled water: $n_2 = 3.27 \times 10^{-20}$ m²/W
- DND 0.1 mg/ml: $n_2 = 3.04 \times 10^{-20}$ m²/W
- **up to 7% of n_2 reduction for DND 0.1 mg/ml**

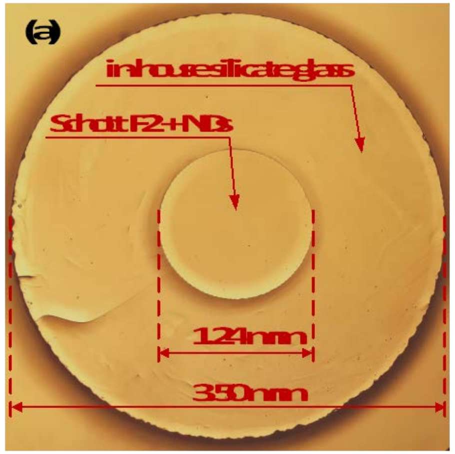
Bulk F2 glass with NDs - fabrication

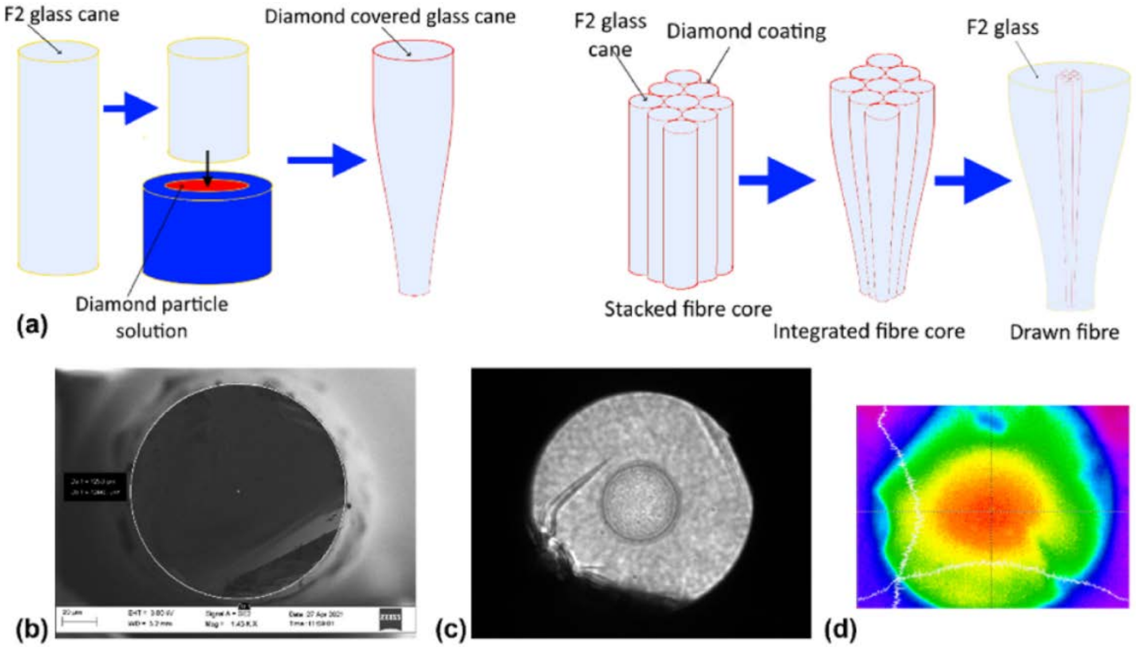
- materials:

  - lead-silicate glass rods (Schott F2), n_d = 1.6199
  - nanodiamonds (MDNV, Adamas Nanotechnologies, 750 nm) suspended in isopropanol
  - modified in-house developed F2 glass with lower RI, n_d = 1.6133

- dip-coating + stack-and-draw method:

  - Schott F2 rods immersed in ND + IPA (10 x)
  - drawing the canes
  - core stacking (**790 rods covered with NDs**) and drawing
  - preform fabrication: core inside the modified F2 tube





sample of the preform

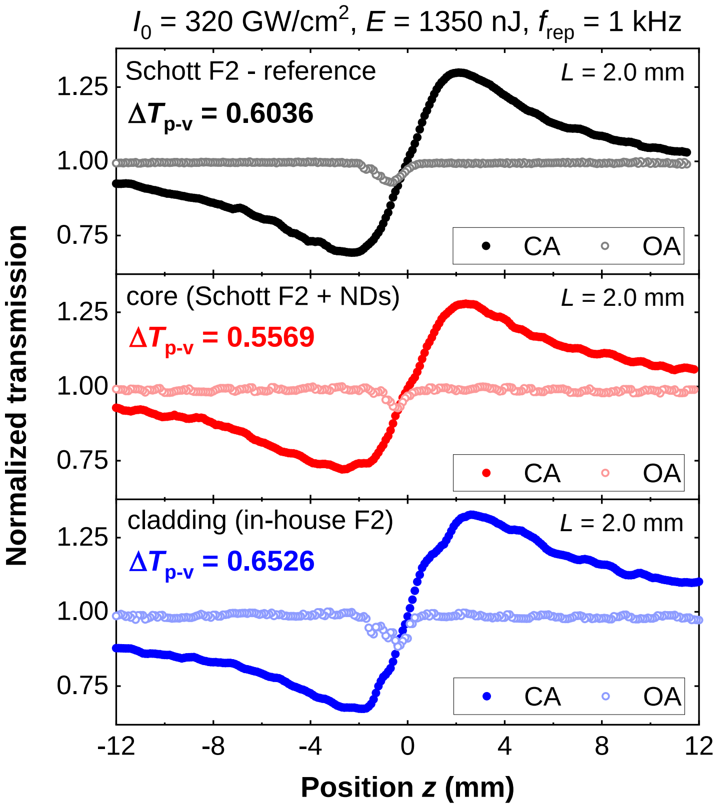
thickness 2 mm

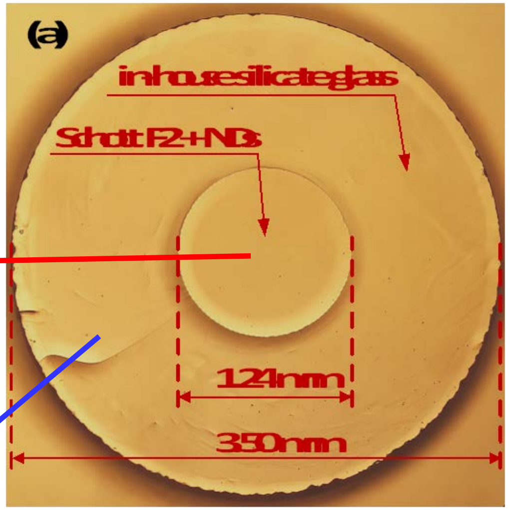
A. Filipkowski, et al.., "Volumetric incorporation of NV diamond emitters in nanostructured F2 glass magneto-optical fiber probes," *Carbon* 196, 10-19, (2022).

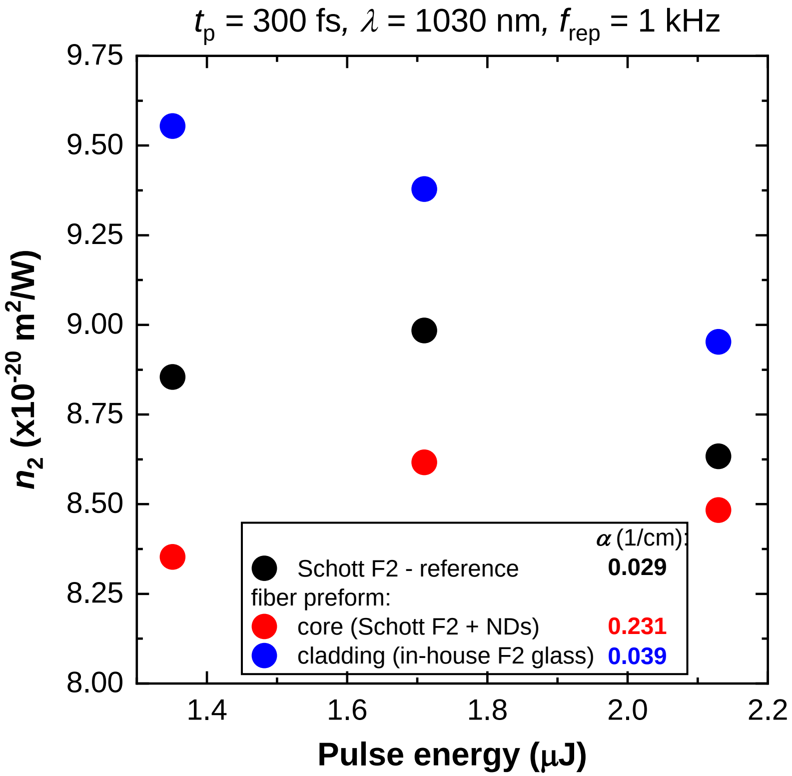
Bulk F2 glass with NDs - nonlinearity

- Z-scan measurement of:
  1. core -> Schott F2 + NDs
  2. cladding -> modified F2 glass
  3. reference Schott F2 glass sample, thickness 2 mm

- 10x higher α in the core (scattering)
- **4% - 7% of n_2 reduction for F2 + NDs glass**







Vitrified silica glass with NDs - fabrication

- materials:

  - detonation nanodiamonds (DND 180 nm) mixed with silica powder in ethanol (10 µg DND per 1 g of silica)
  - silica tube

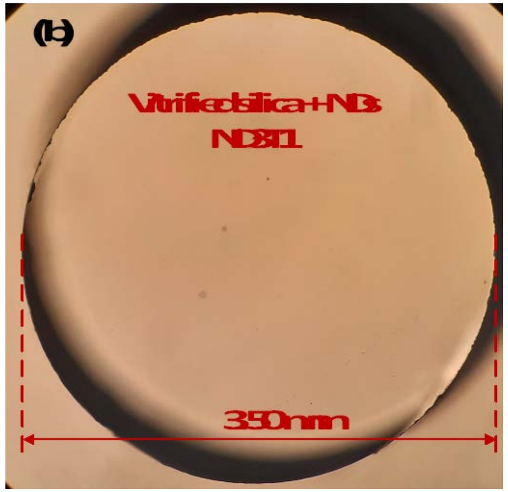
- CO_2 laser vitrification process

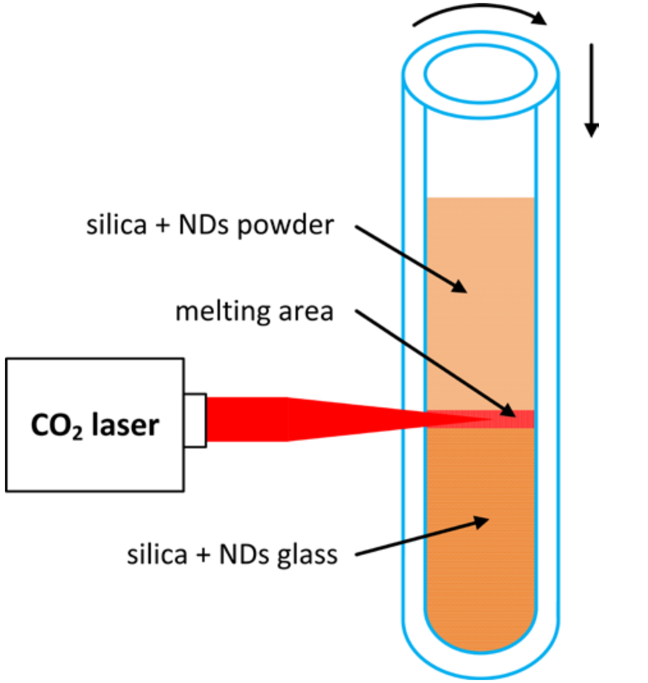
  - DND + silica mixture drying
  - heating DND + silica powder in silica tube (600°C)
  - laser vitrification along the capillary with powder
  - not uniform preforms due to process modification

Prof. Alex Heidt

two-sided polished sample of the preform

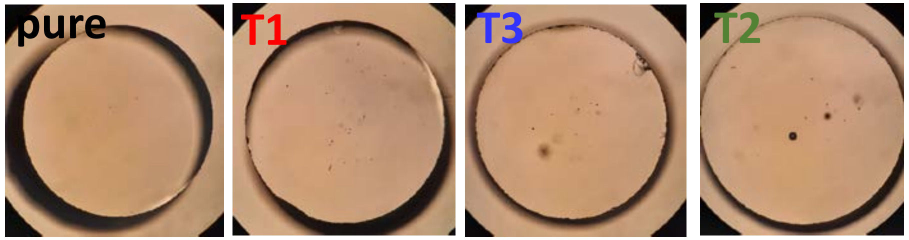
thickness 2 mm

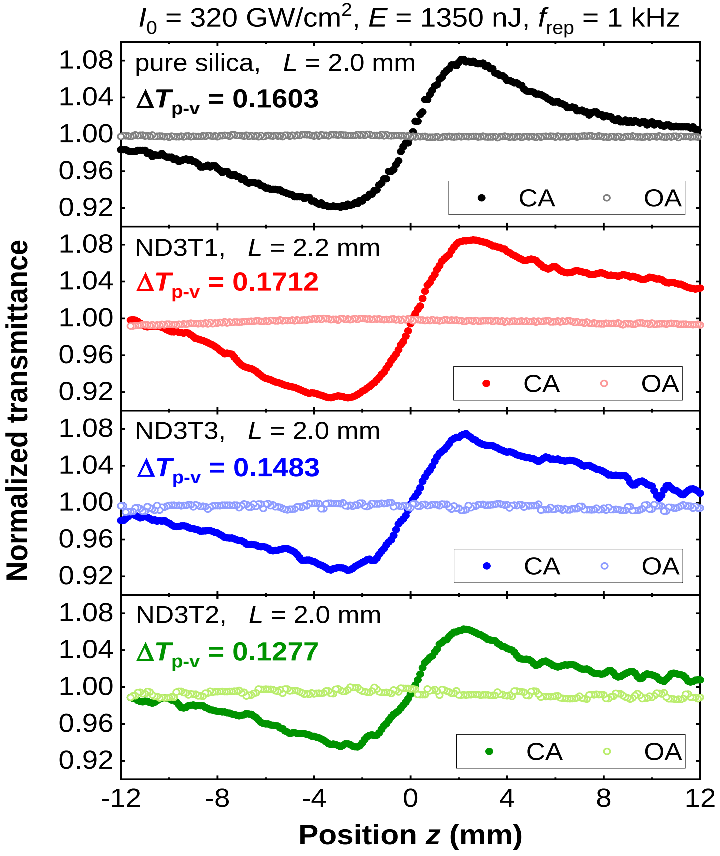


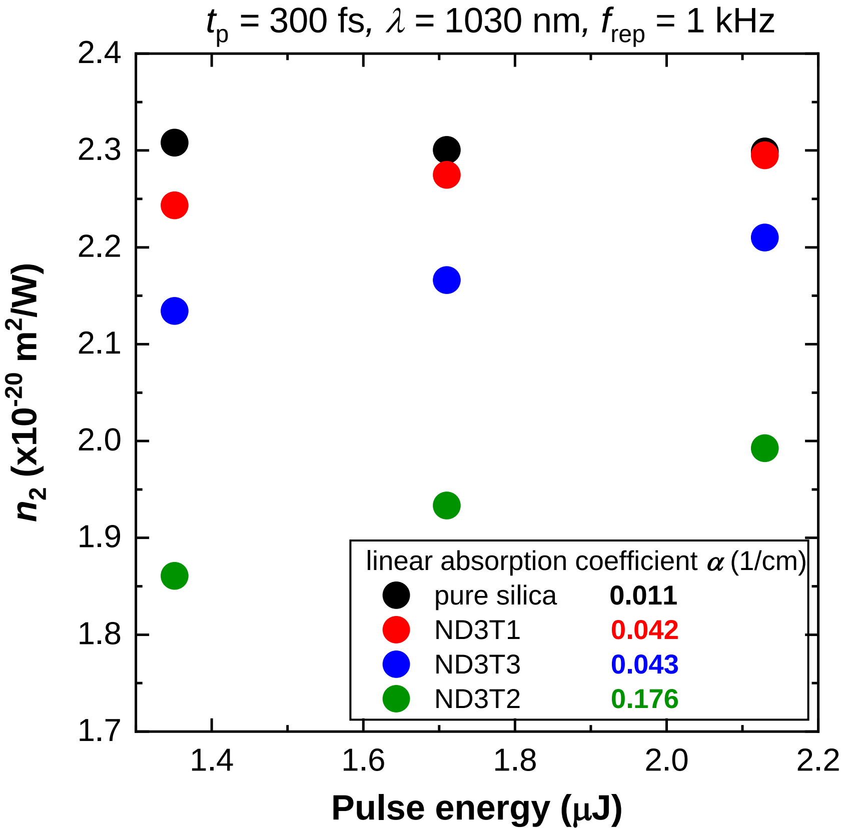


Vitrified silica glass with NDs - nonlinearity

- Z-scan measurement of:
  1. vitrified pure silica glass
  2. vitrified silica glass with NDs (samples ND3T1-3)



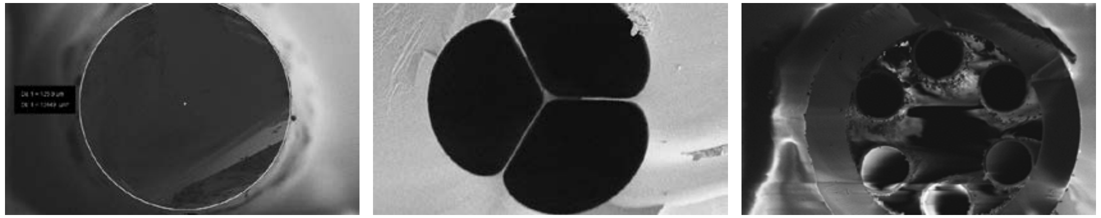




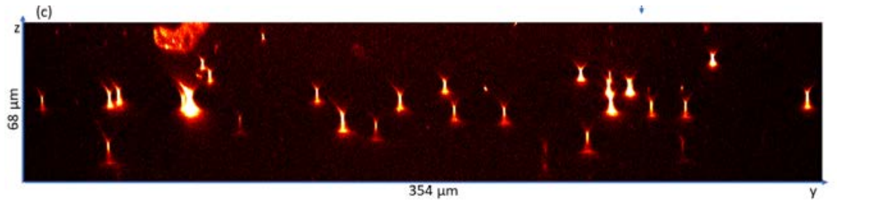
- vitrified silica has the same n_2 as commercial fiber grade silica glass
- all samples with NDs have higher α and lower n_2 than pure silica
- possibly inhomogeneous ND dopant
- **13% - 19% of n_2 reduction for ND3T2 sample**

Conclusions 1/2

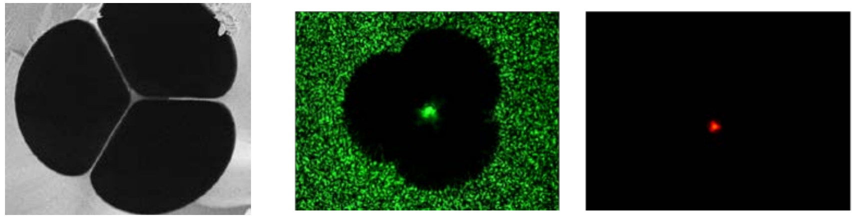
- Volumetric functionalization of optical fibers with nanodiamonds enables practical magnetic field sensors across diffrent fiber geometries



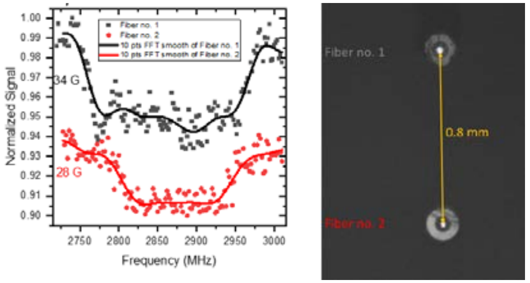
- Modified stack-and-draw fiber development enables control of diamond partice distribution at the micro-scale



- Diamond’s NV fluorescence can be effectively captured and guided in strongly confining fibers



- Magnetic field gradient information is obtainable using randomly oriented spins in nanodiamond - towards vector measurements?



Conclusions 2/2

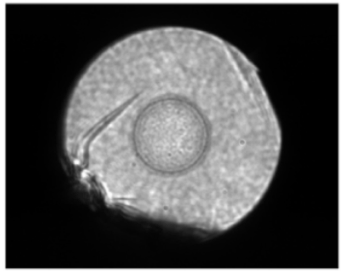
- Nanodiamonds decrease nonlinear index of refraction in all examined host materials:

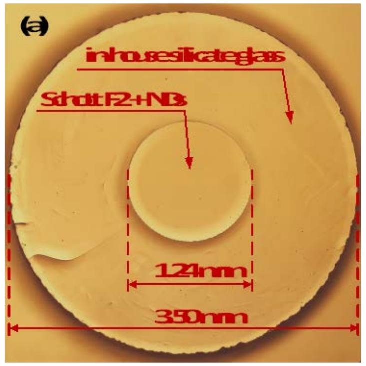
  - water **4.5% ÷ 7.0%** (0.8 μJ)
  - Schott F2 glass **4.2 %** (1.7 μJ)
  - vitrified silica glass **1.0 % ÷ 16%** (1.7 μJ)

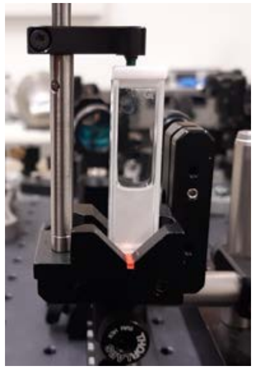
- Fabricated hybrid glass with NDs are useful for optical fiber development

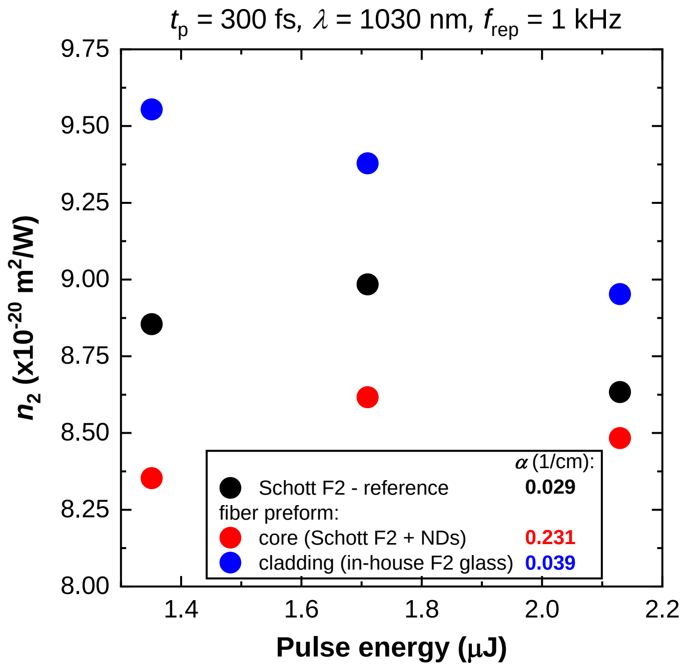
- Nonlinearity can be controlled by NDs particle size, surface functionalization and concentration

- Further reduction of n_2 may result high loss (a zero nonlinear fiber can be a challenge)









UNIVERSITY OF WARSAW

FACULTY OF PHYSICS
UNIVERSITY OF WARSAW

JAGIELLONIAN UNIVERSITY IN KRAKÓW

GDAŃSK UNIVERSITY OF TECHNOLOGY

Łukasiewicz

ACKNOWLEDGEMENTS

TEAM NET Programme POIR.04.04.00-00-1644/18

European Funds
Smart Growth

FNP Foundation for Polish Science

European Union
European Regional Development Fund

QUNNA
www.qunna.pl