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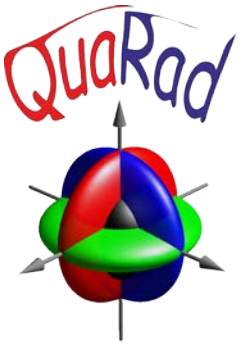


Photon triplet generation in photonic crystal fibres

Andrea Cavanna, C. Okoth, M. Frosz, G. Leuchs, M.V. Chekhova, N. Y. Joly, and Philip St.J. Russell

MPL Erlangen, Germany

DFG Deutsche Forschungsgemeinschaft

Outline

- Photon triplet generation
  - Introduction
  - Motivation
  - Wigner function
  - Structure
  - Characteristics
  - Third-harmonic generation
  - Photon triplet phase matching
- Tapered fibre
  - Structure
  - Characteristics
  - Third-harmonic generation
  - Photon triplet phase matching
- Hybrid solid core fibre
- Hollow core fibre
- Summary – Conclusions

Introduction

Third harmonic generation:

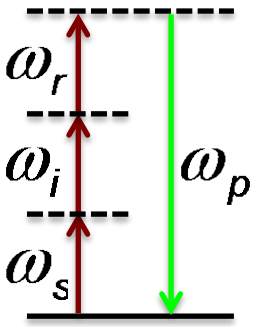
$$P_{3\omega} \propto \gamma^2 L^2 P_\omega^3 \mathrm{sinc}^2(\Delta kL/2)$$

$$\gamma \propto \chi^{(3)} J_3$$

Overlap integral:

$$J_3 = \iint_{A_{NL}} (F_\omega^* \cdot F_{3\omega})(F_\omega^* \cdot F_\omega^*) dS$$

ω 3ω



Energy and momentum conservation:

$$\Delta k = k_p - k_s - k_i - k_r = 0$$

$$\omega_p = \omega_s + \omega_i + \omega_r$$

Introduction

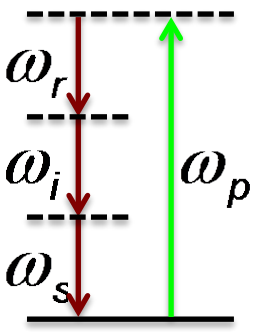
Third harmonic generation:

$$P_{3\omega} \propto \gamma^2 L^2 P_{\omega}^3 \mathrm{sinc}^2(\Delta kL/2)$$

$$\gamma \propto \chi^{(3)} J_3$$

Triplet generation:

$$P_{\omega} \propto \gamma^2 L^2 P_{3\omega} \mathrm{sinc}^2(\Delta kL/2)$$



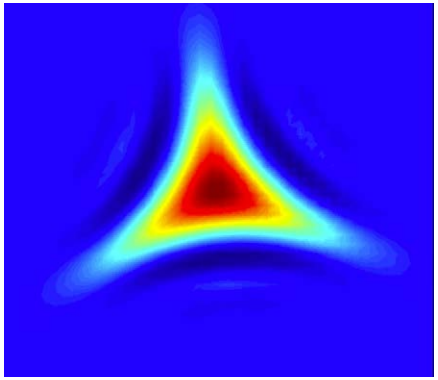
Energy and momentum conservation:

$$\Delta k = k_p - k_s - k_i - k_r = 0$$

$$\omega_p = \omega_s + \omega_i + \omega_r$$

Motivation

- Novel effect
- Non-Gaussian squeezed state
- Wigner function negativity
- Quantum information
  - Heralded two photon source
  - Three-party quantum secure direct communication



Wigner function

Two photon state:

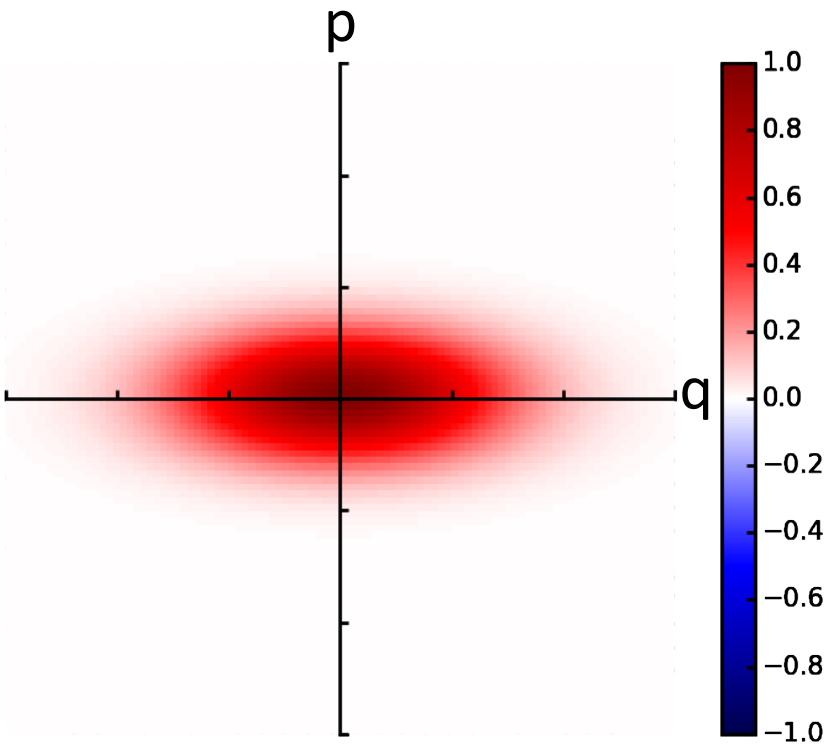
$$|\psi\rangle = c_0 |0,0\rangle + c_1 |1,1\rangle + \ldots$$

Equations of motion:

$$\frac{dq}{dt} = 2\Gamma q$$

$$\frac{dp}{dt} = -2\Gamma p$$

Γ: parametric gain



Wigner function

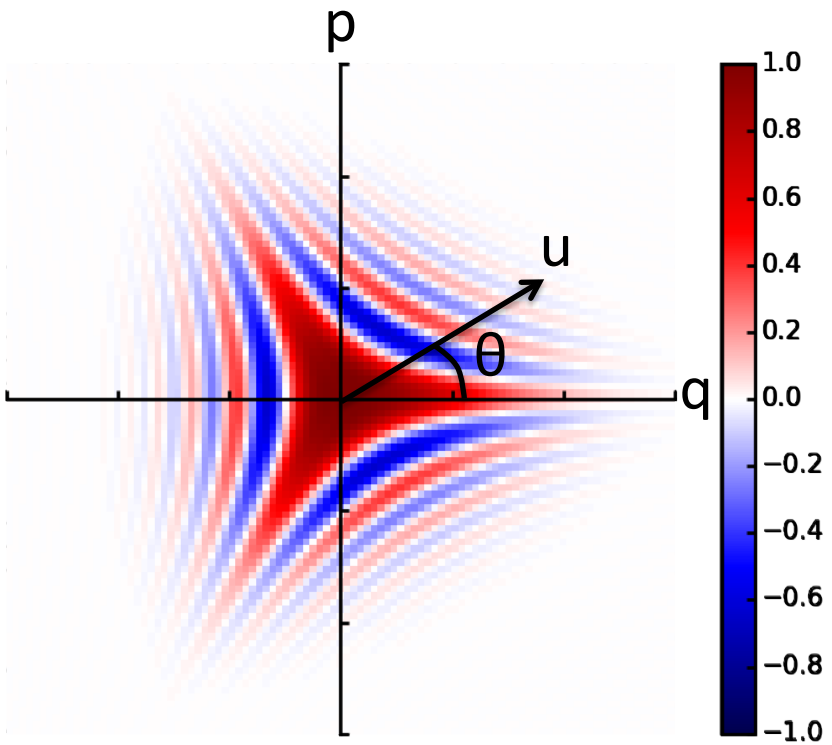
Three photon state:

$$\left|\psi\right\rangle = c_0\left|0,0,0\right\rangle + c_1\left|1,1,1\right\rangle + \ldots$$

Equations of motion:

$$\frac{du}{d\tau} = 3u^2\cos(3\theta)$$

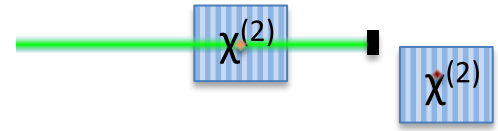
$$\frac{d\theta}{d\tau} = -3u\sin(3\theta)$$



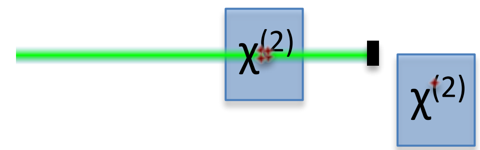
K. Banaszek, and P. L. Knight, PRA **55**, 2368-2375 (1997)

State of the art

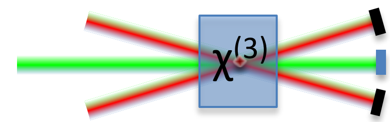
- Cascaded SPDC



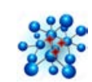
- SPDC + up-conversion



- Seeded triplet generation



- Quantum dots



- Spontaneous generation in microwaves

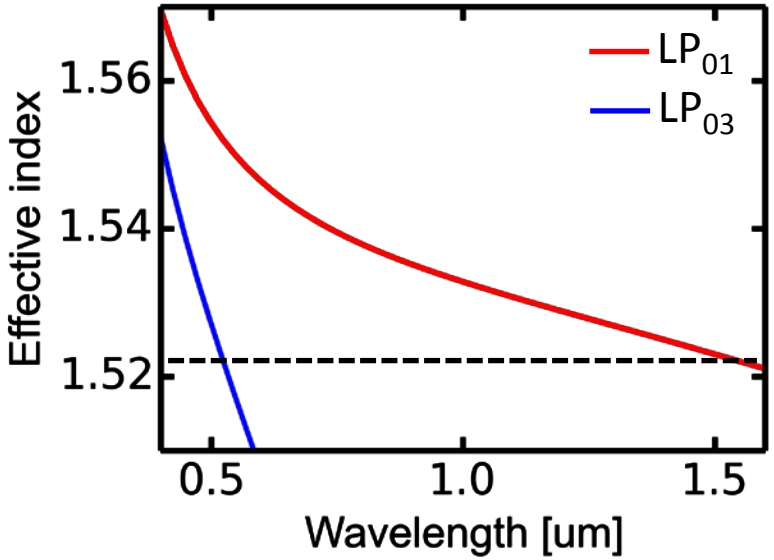
[illegible] Tamarat, D. Lounis, P. Poole, G. Weihs, and H. Majedi, Nat. Comm. **8**, 15716 (2017).

Challenges

$$P_\omega \propto (\chi^{(3)} J_3)^2 L^2 P_{3\omega} \mathrm{sinc}^2(\Delta kL/2)$$

- $\chi^{(3)}$: high values of nonlinearity also correspond to high absorption and luminescence
- J_3 : can be strongly reduced in case of inter-modal phase-matching

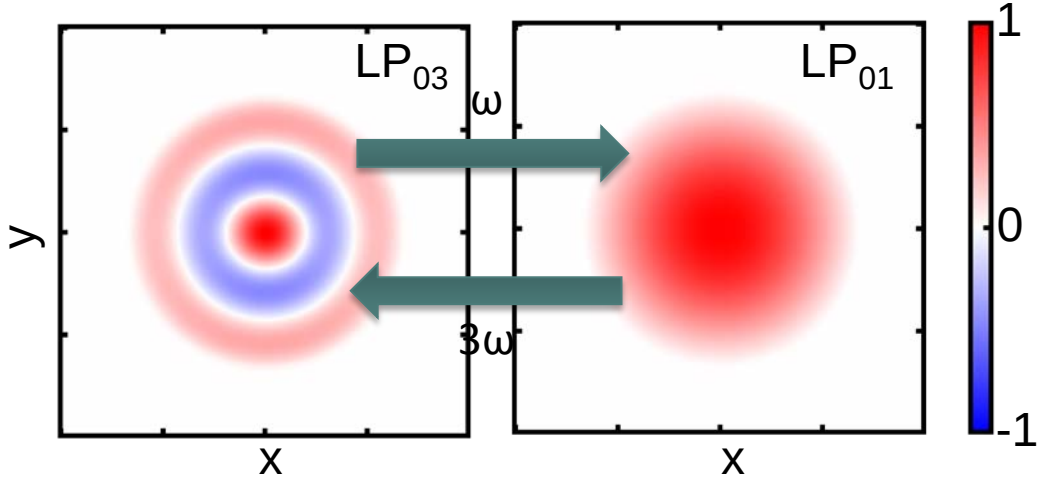
Inter-modal phase-matching



$$\Delta k = 0$$

$$k = n_{eff}\frac{\omega}{c}$$

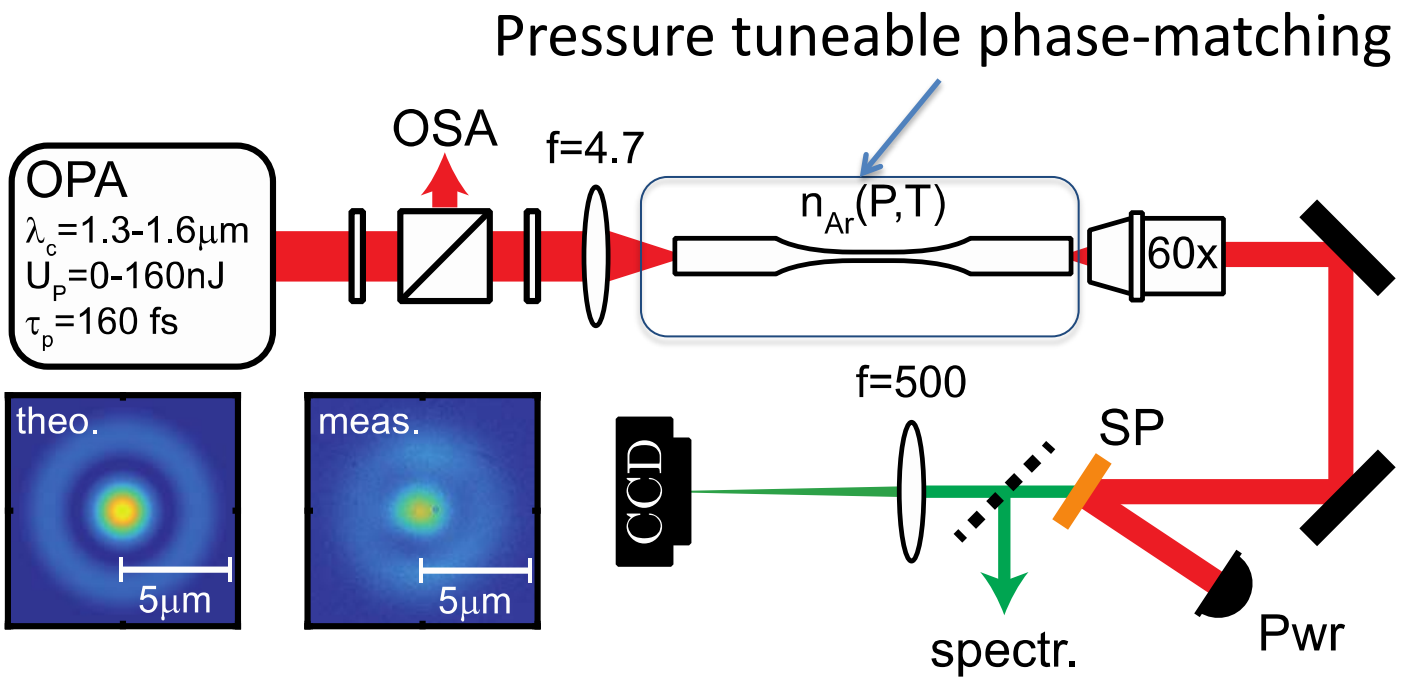
$$n_{eff}(\omega) = n_{eff}(3\omega)$$



Fibre types

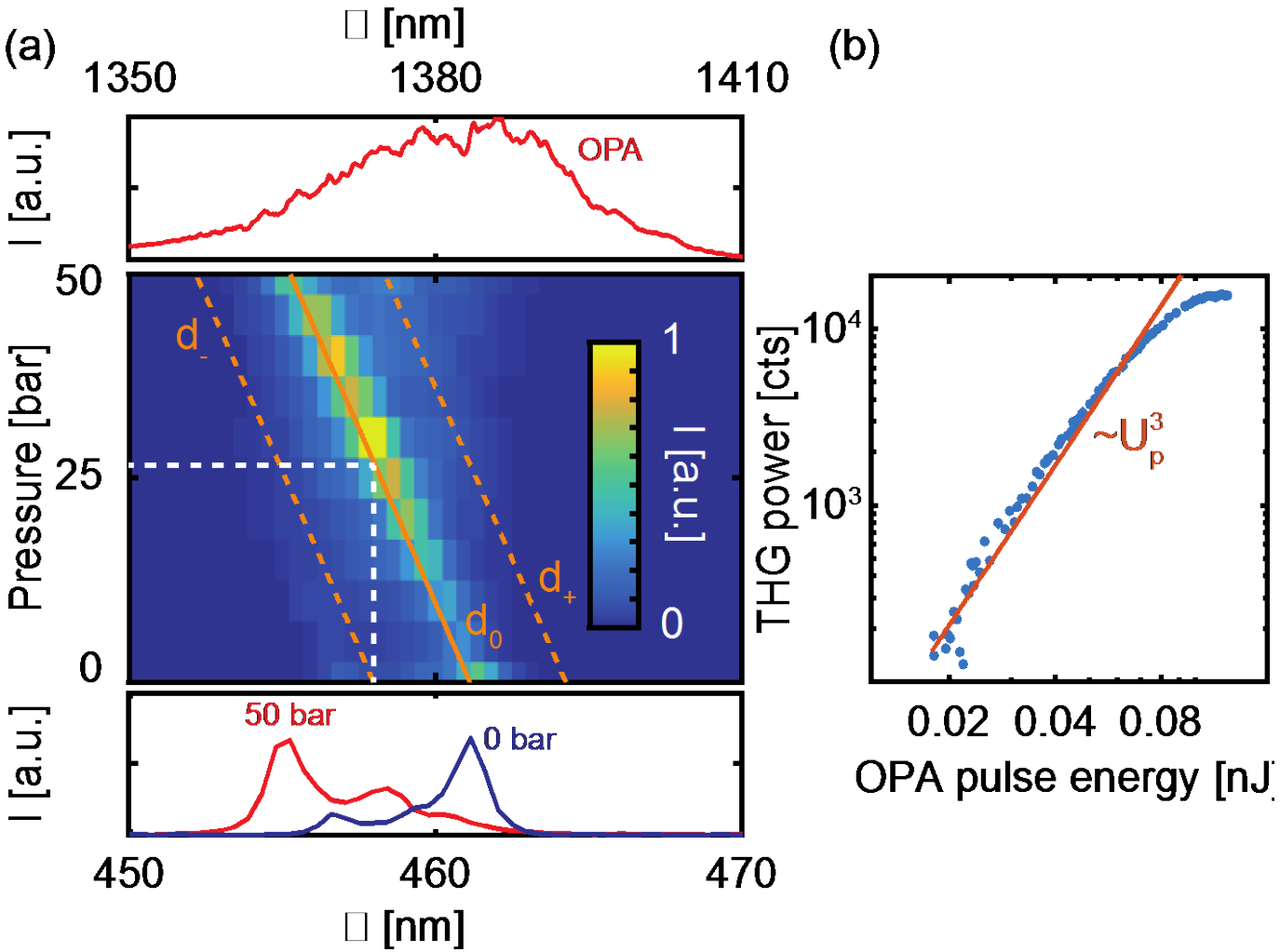
- Tapered fibre → High overlap integral and ‘tuneable’ phase-matching.
- Hybrid fibre → High overlap integral between Gaussian-like modes.
- Hollow core fibre → Tuneable phase-matching and high damage threshold.

Tapered fibre



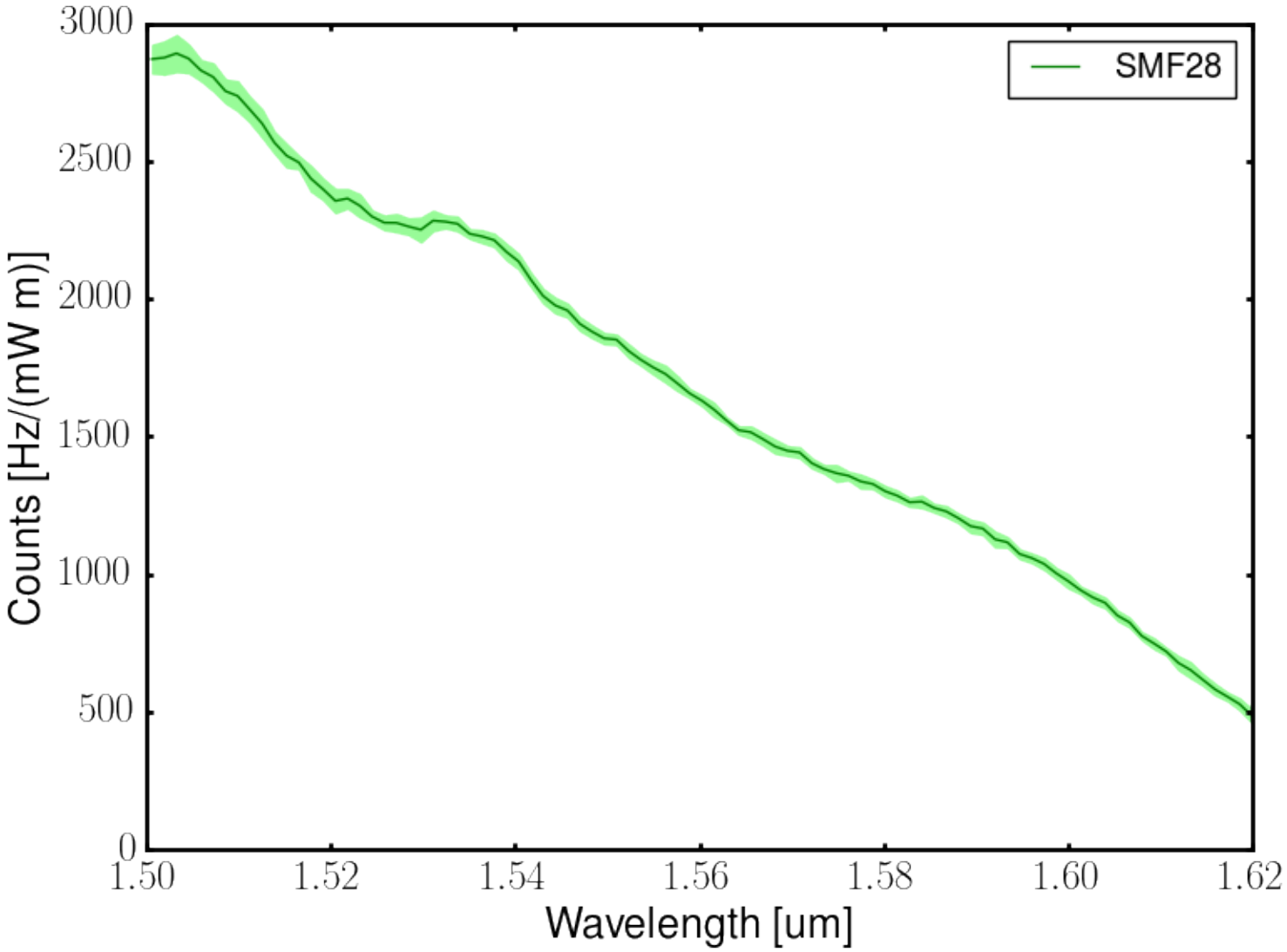
J. Hammer, A. C., R. Pennetta, M. V. Chekhova, P. St.J. Russell, and N. Y. Joly, Opt. Lett. (2018) accepted.

Tapered fibre

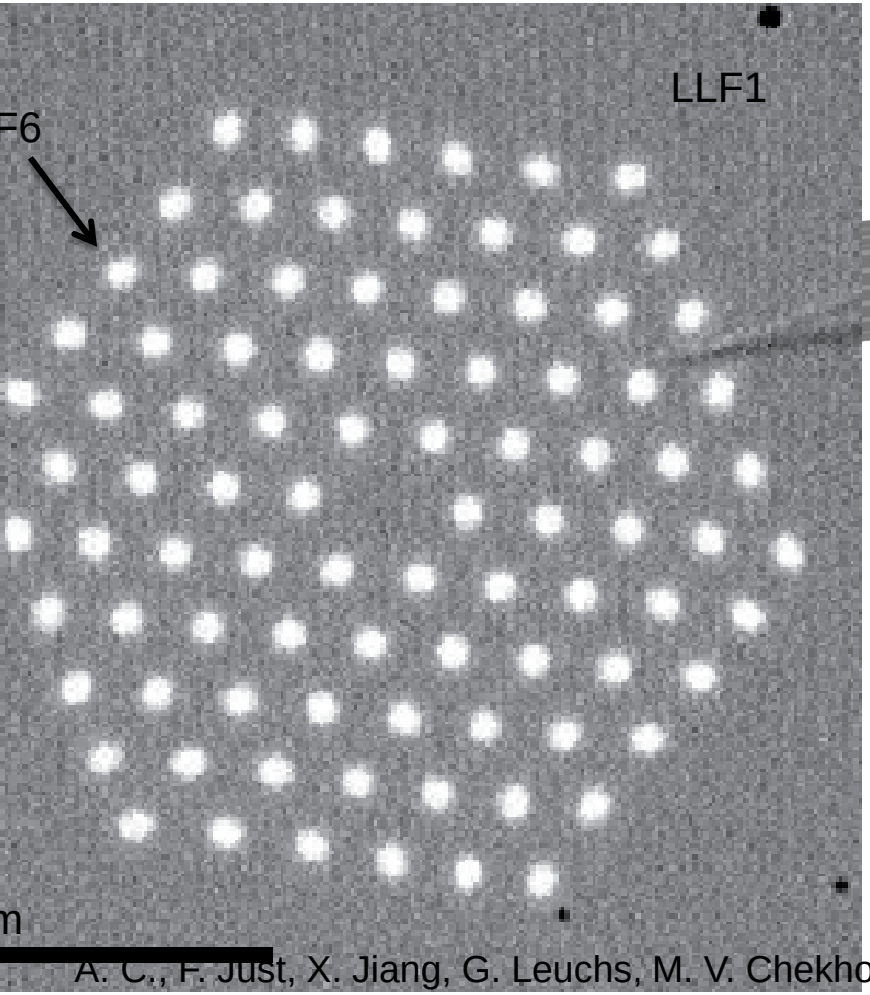


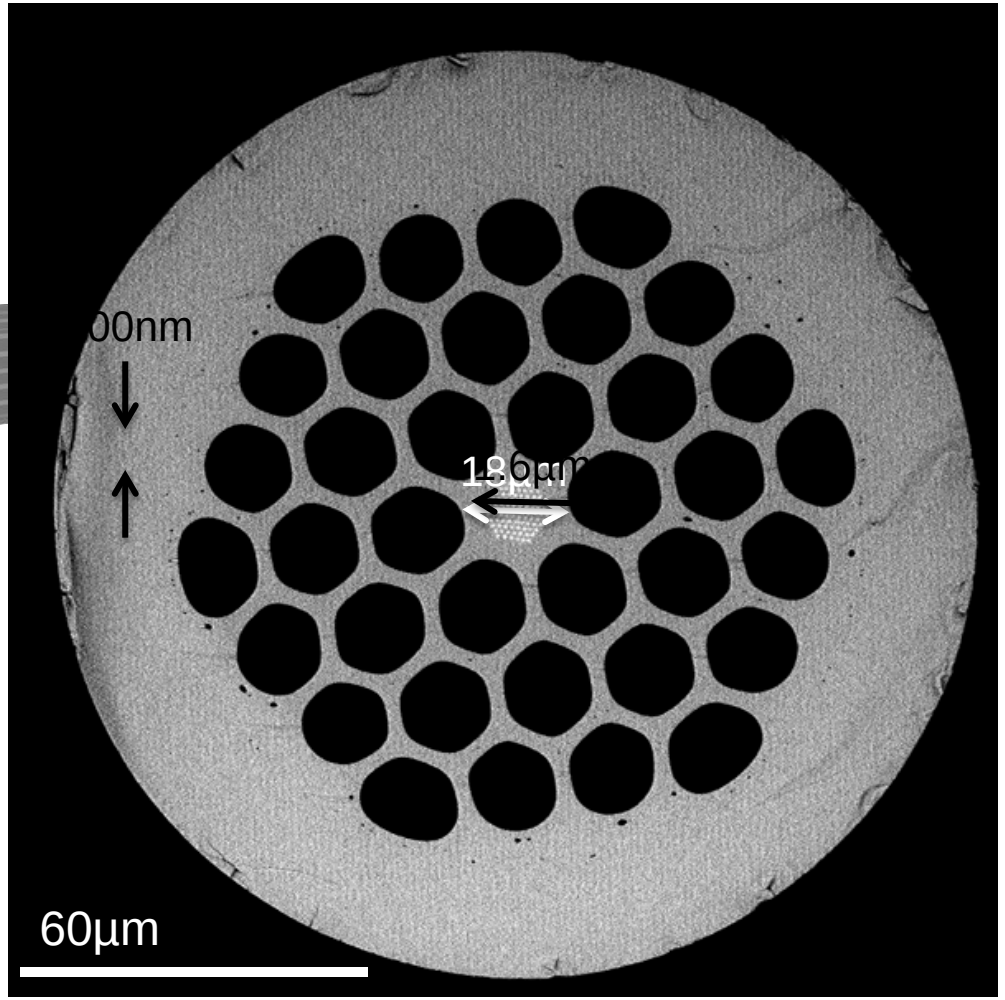
J. Hammer, A. C., R. Pennetta, M. V. Chekhova, P. St.J. Russell, and N. Y. Joly, Opt. Lett. (2018) accepted.

Luminescence



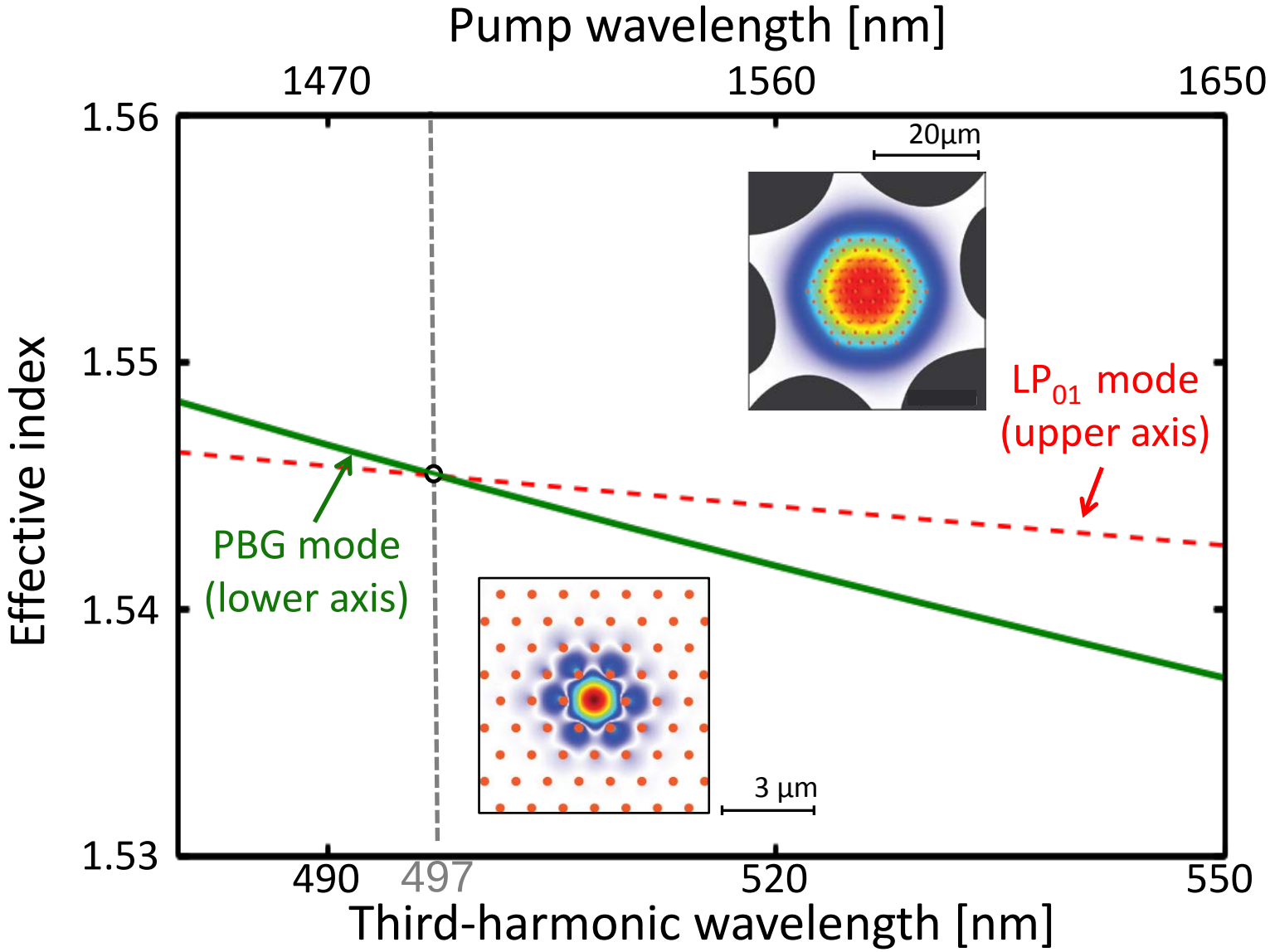
Hybrid Fibre



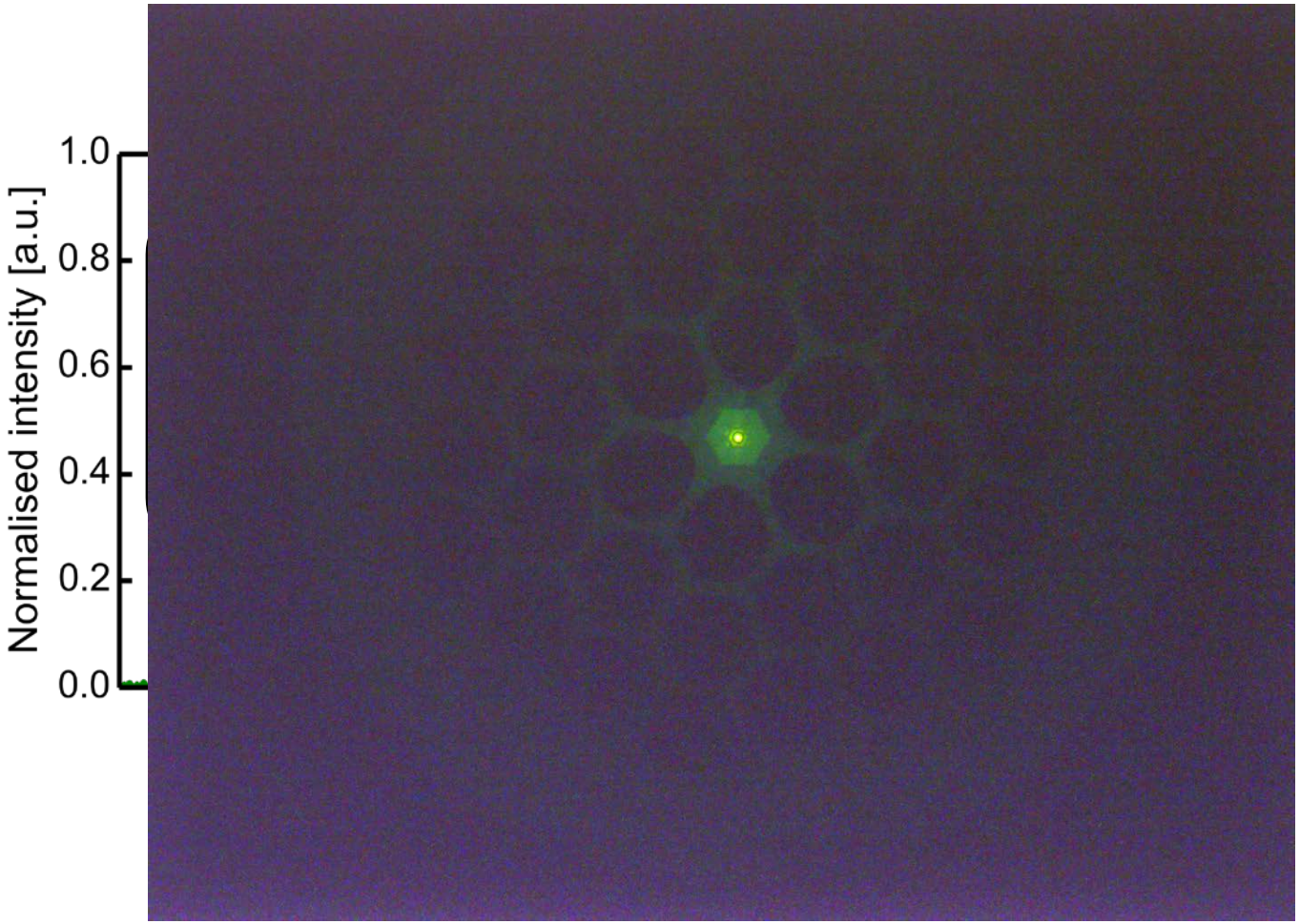


A. C., F. Just, X. Jiang, G. Leuchs, M. V. Chekhova, P. St.J. Russell, and N. Y. Joly, Optica **3** (9) 952-955 (2016).

Third-harmonic generation



Third-harmonic generation



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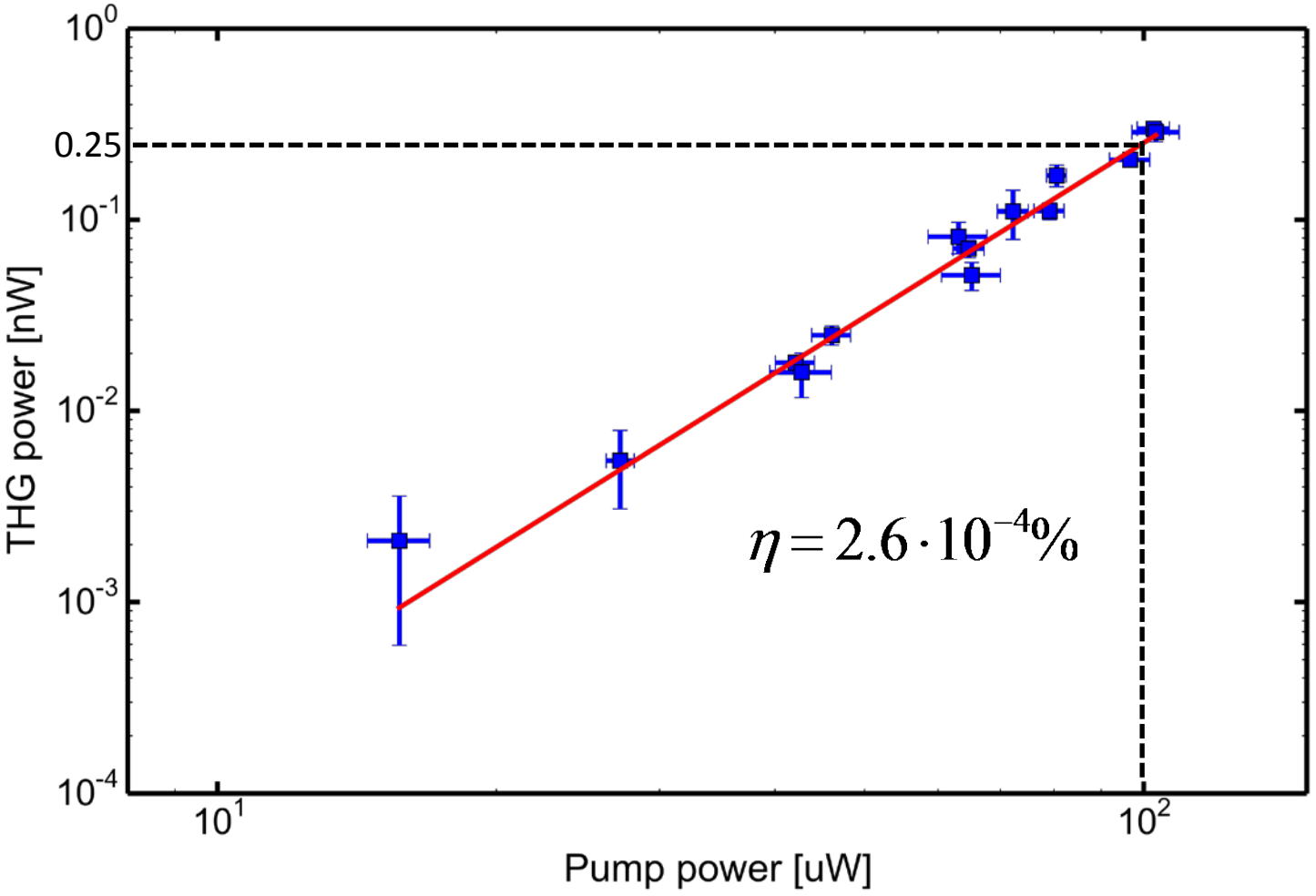
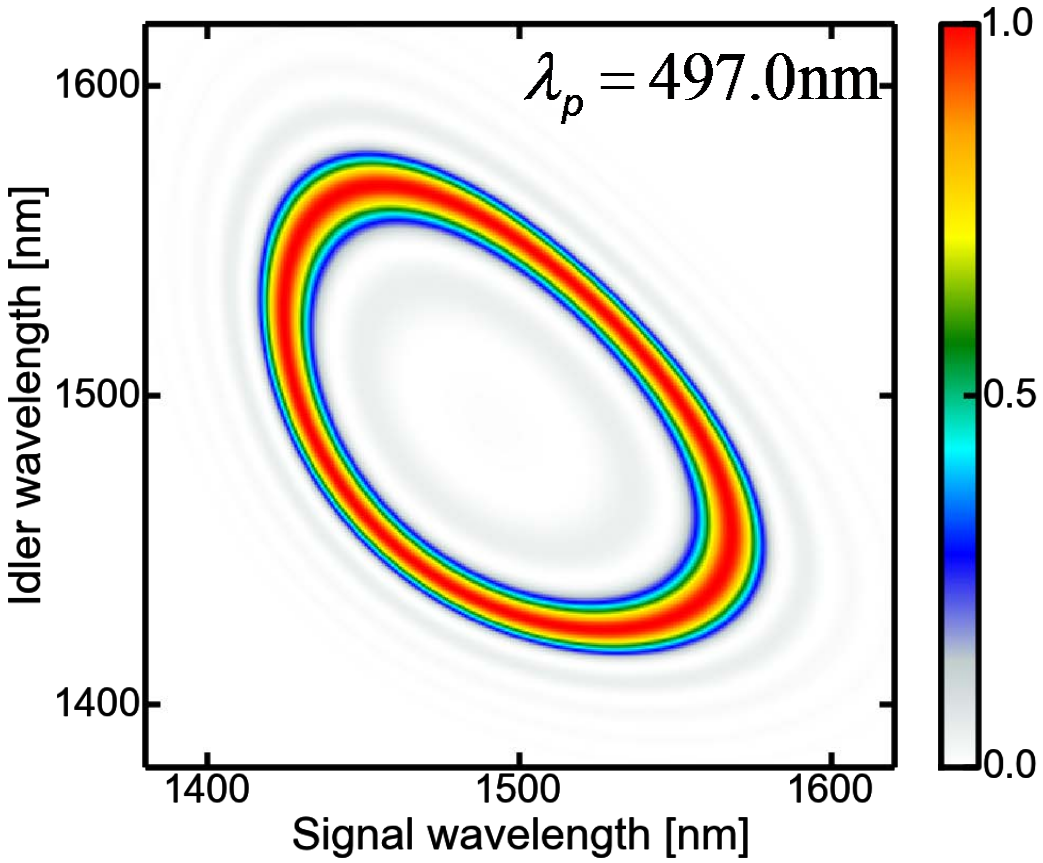
Third-harmonic generation

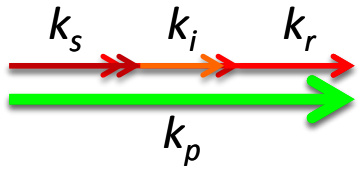


Photon triplet generation



Phase matching function:

$$\text{sinc}^2\left(\Delta kL/2\right)$$



$$L = 10\text{cm}$$

$$P_{3\omega} = 200\text{mW}$$

$$N_\omega \approx 50 \text{ triplets/s}$$

M. Corona, K. G. Palmett, and A. B. U'Ren, PRA **84**, 033823 (2011)

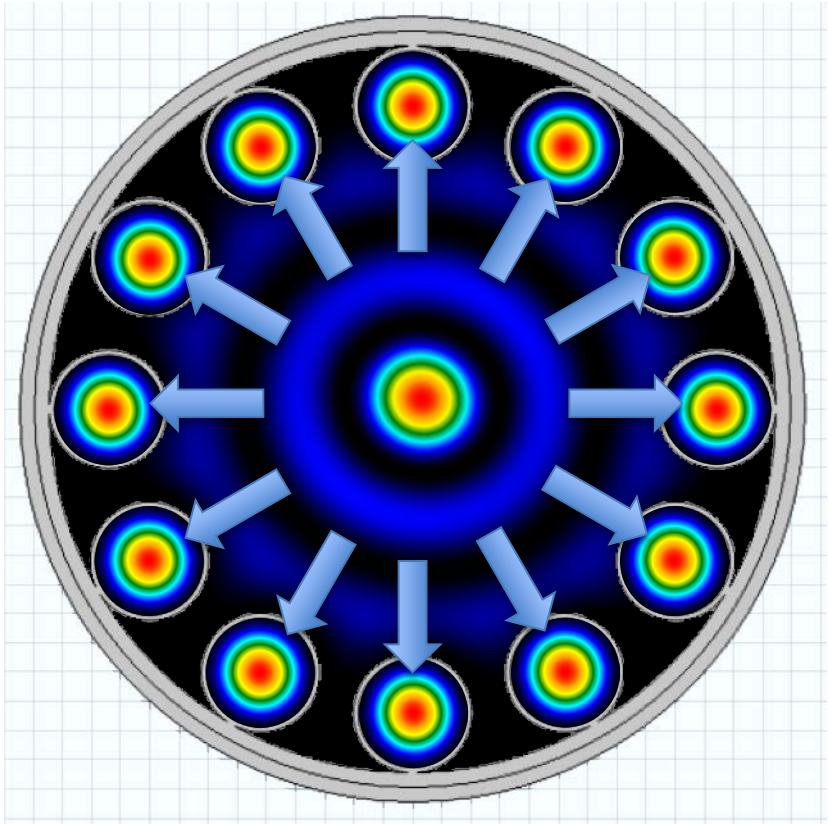
Hollow core fibres

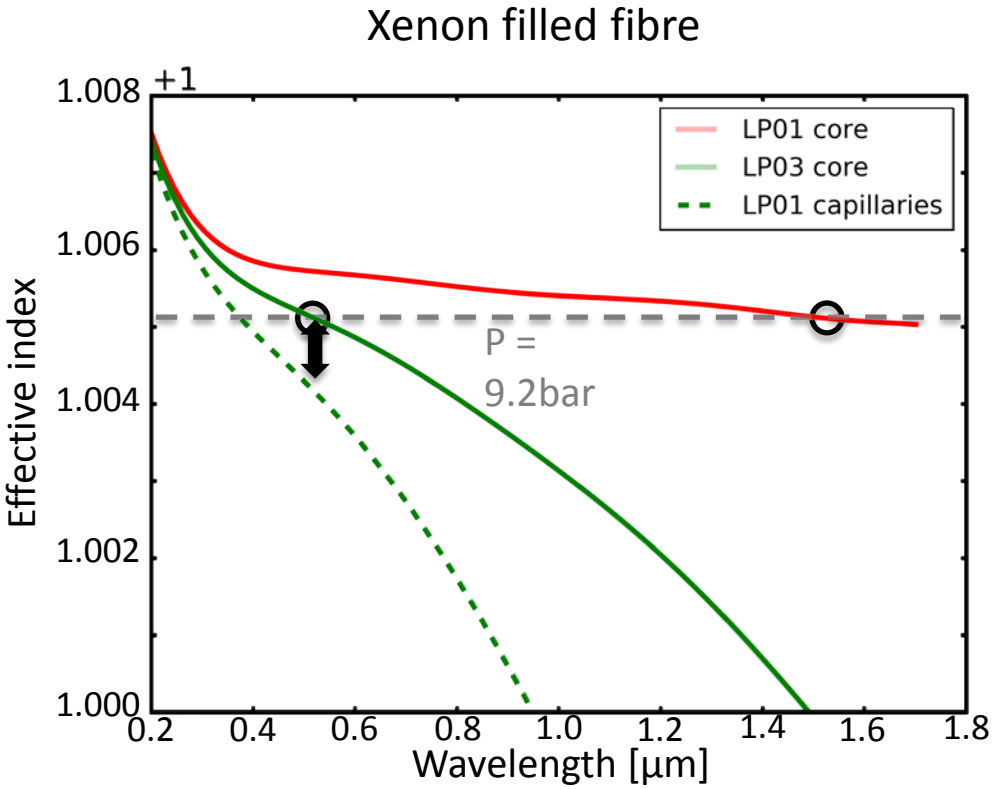
Features:

- Pressure controlled phase-matching.
- Filled with noble gas as nonlinear material.
- Very high damage threshold.
- Almost no luminescence

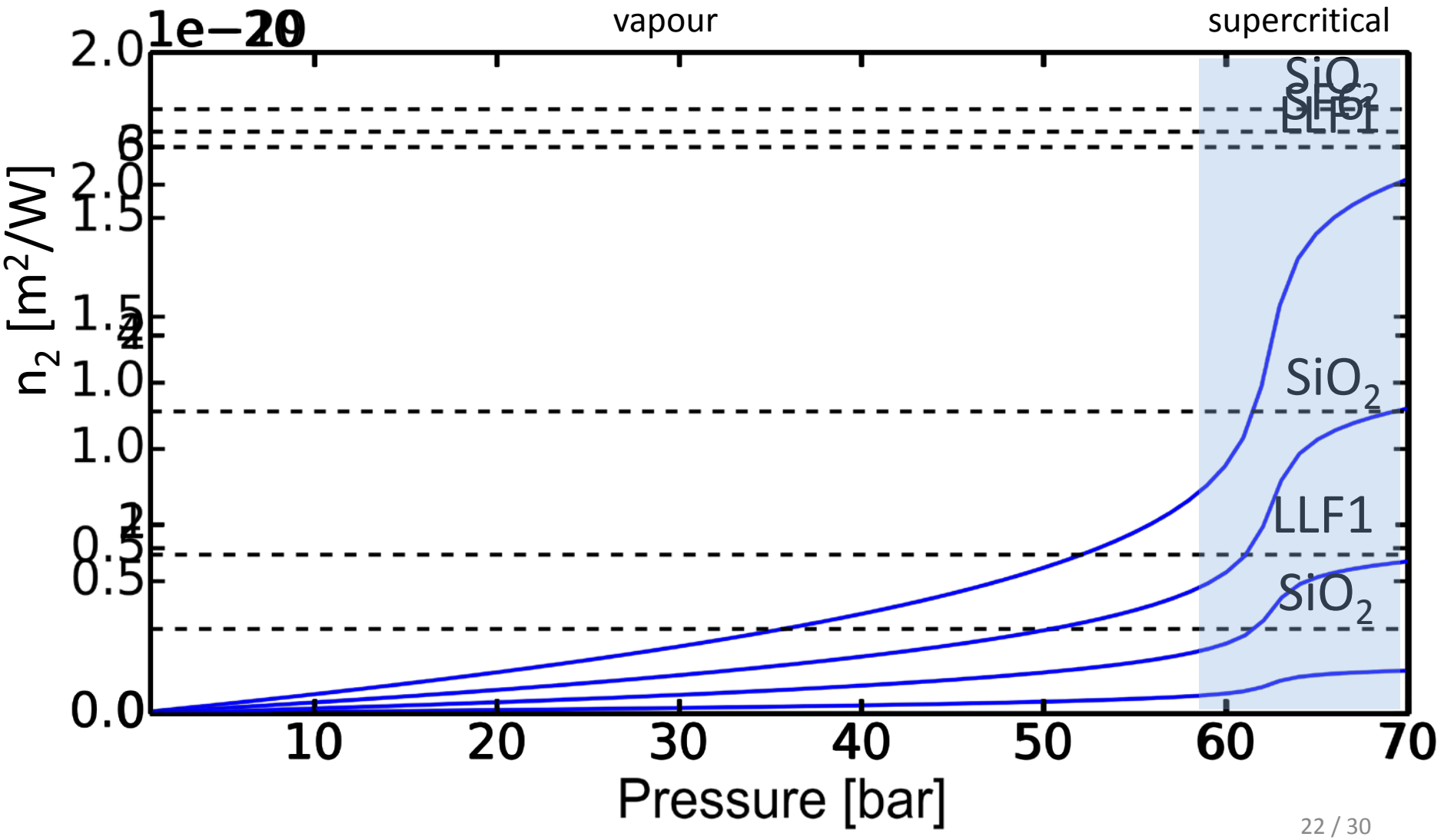
P. Übel, M. C. Günendi, M. H. Frosz, G. Ahmed, N. N. Edavalath, J.-M. Ménard, and P. St.J. Russell, Opt. Lett. **41**, 1961 (2016) .

Hollow core fibre

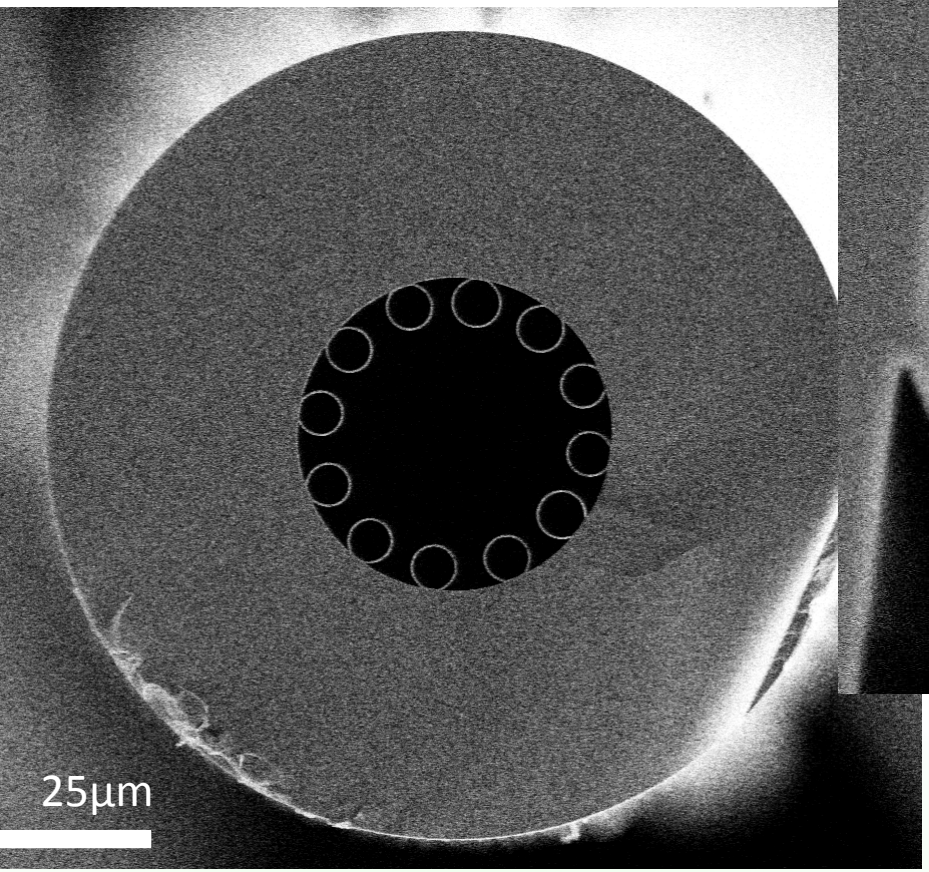


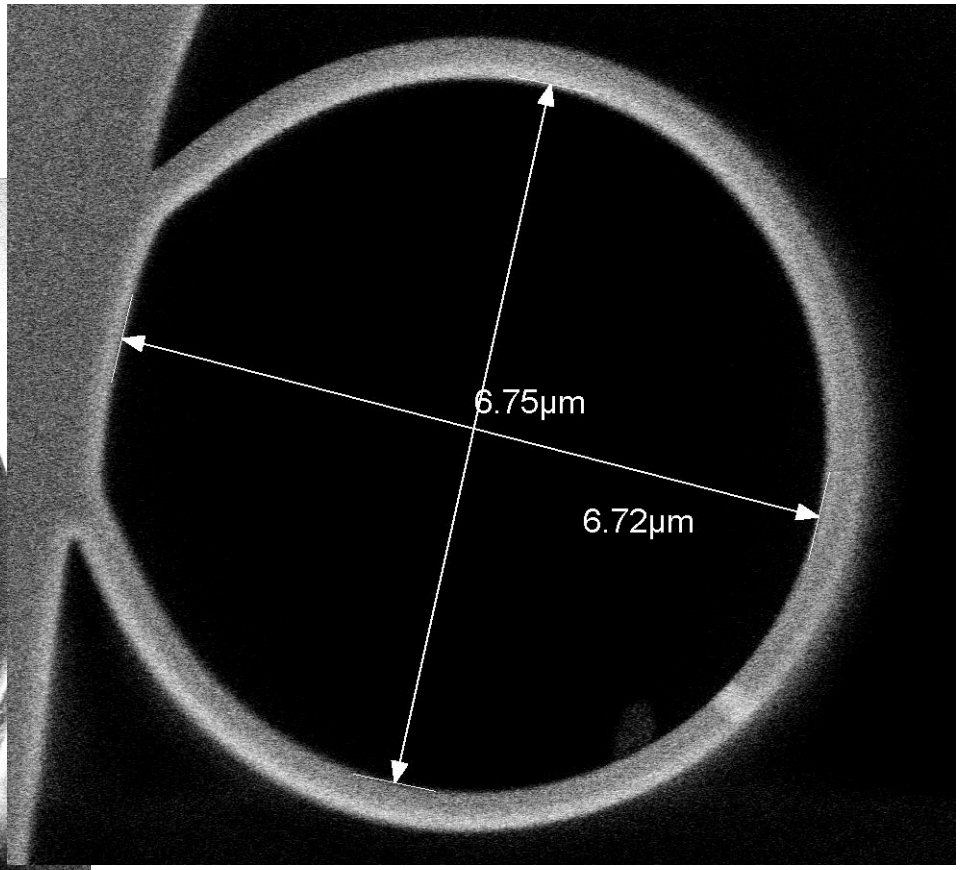


Xenon nonlinearity

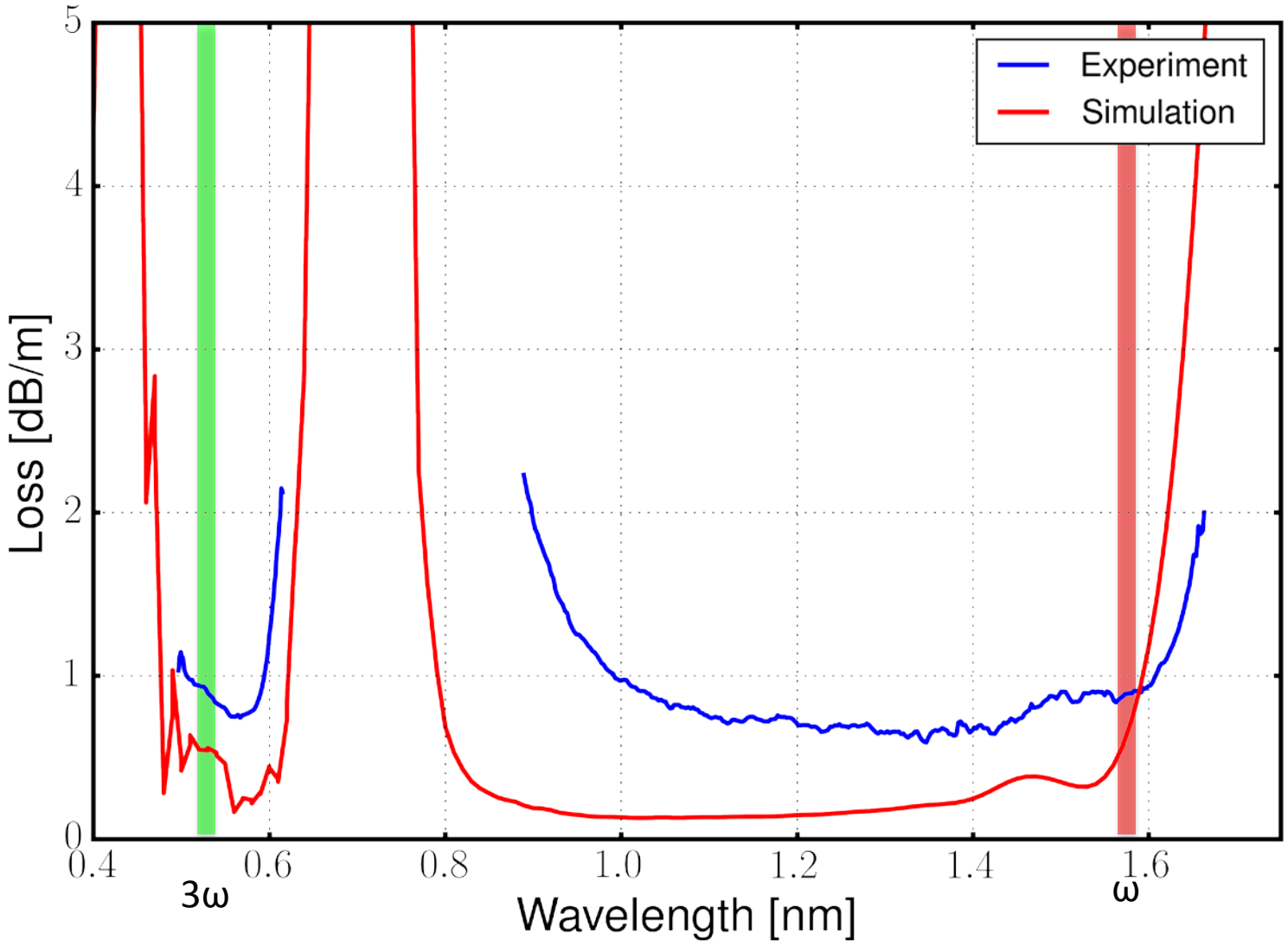


Single-ring fibre

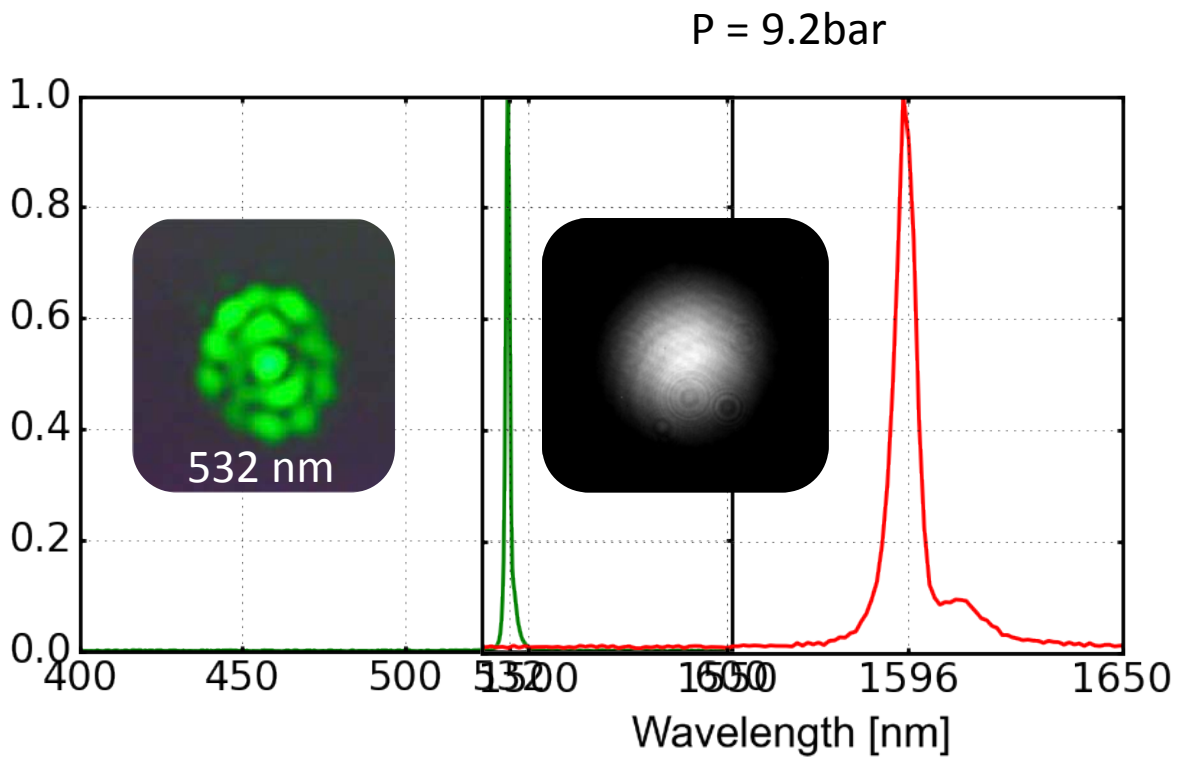




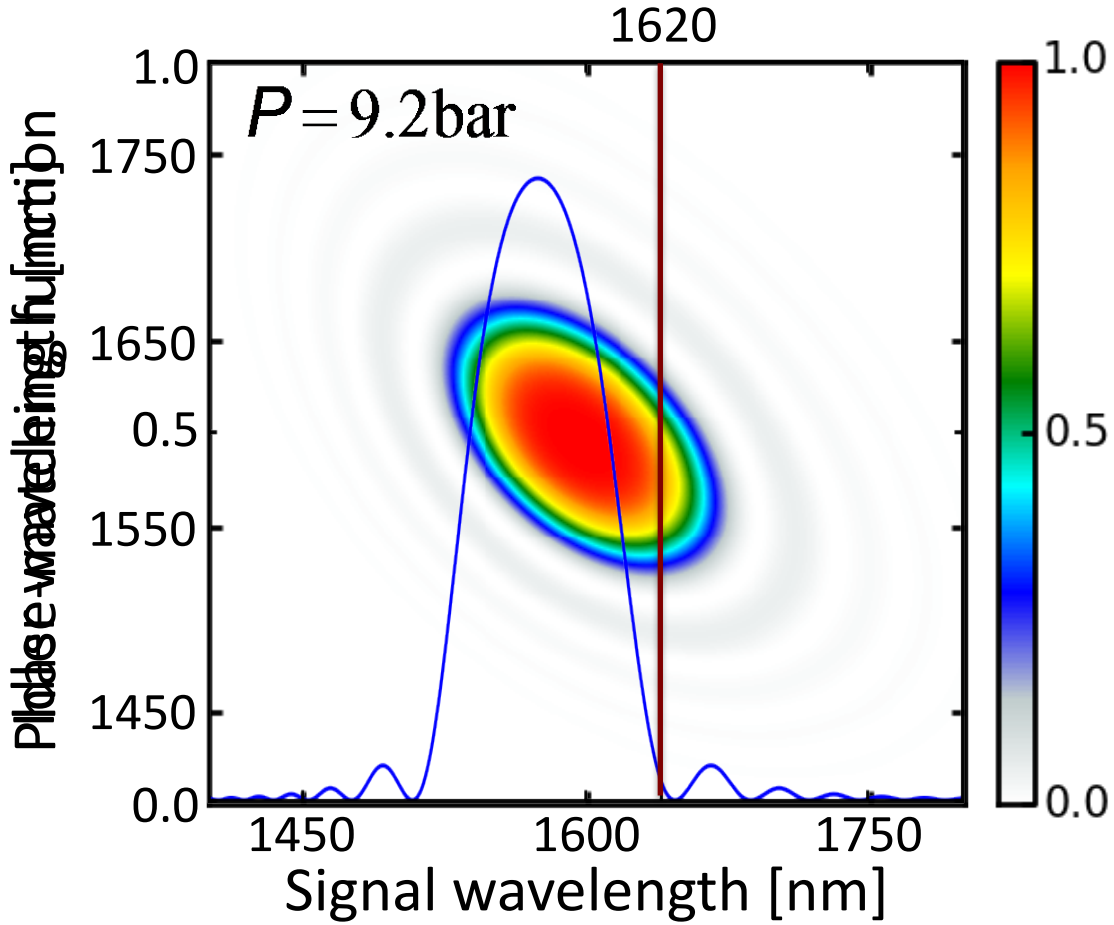
Measurement losses



Third-harmonic generation



Photon triplet generation



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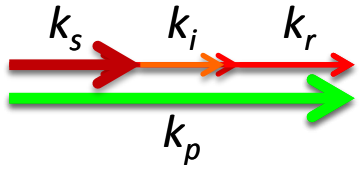


$L = 1\text{m}$

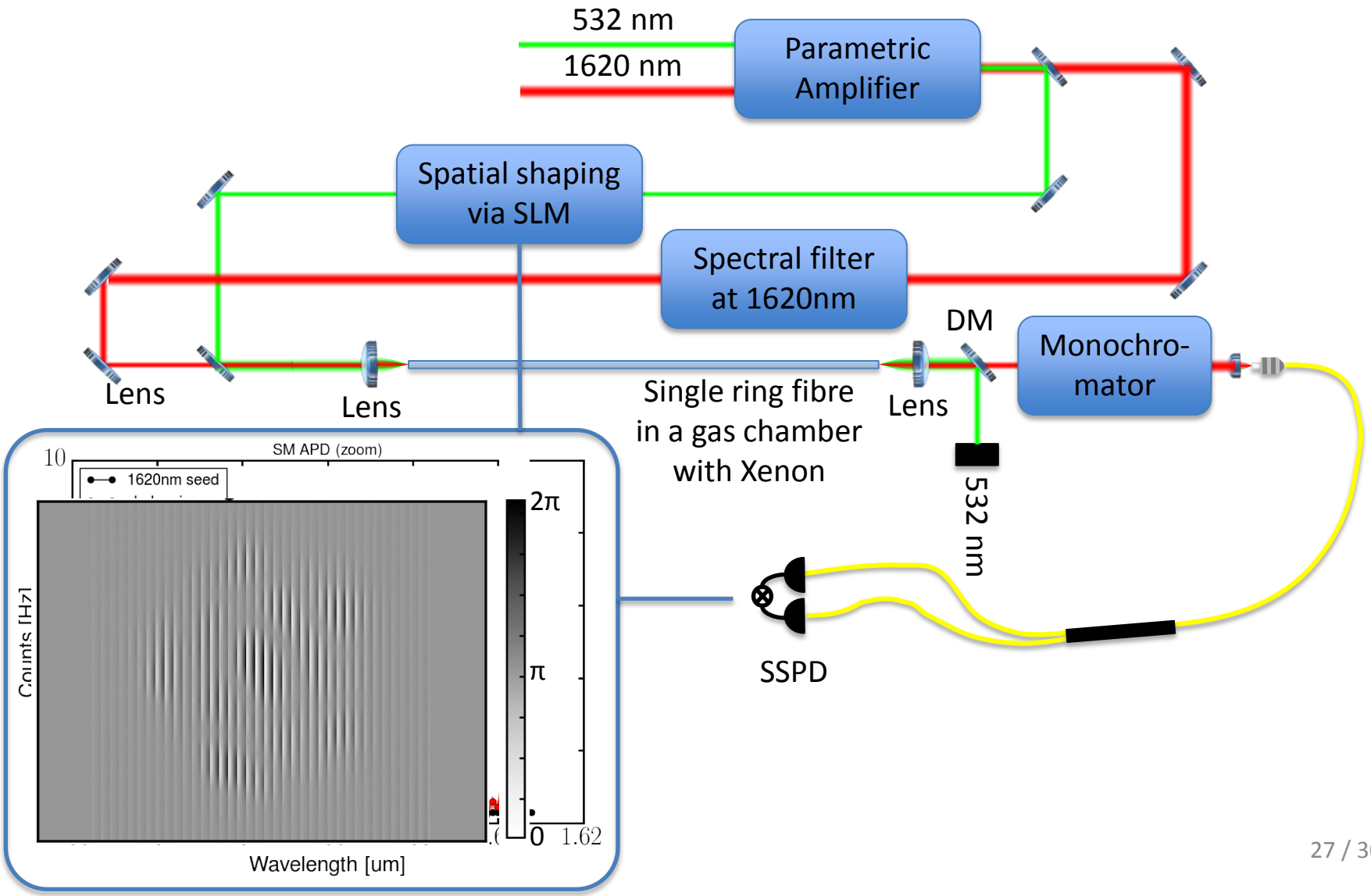
$P_{3\omega} = 0.5\text{W}, 1\text{kHz}, \ 20\text{ps}$

$P_{seed} = 10mW$

$N_{\omega} \approx 10^4$ triplets/h

M. Corona, K. Garay-Palmett, and A. B. U'Ren, PRA **84**, 033823 (2011)

Set-up


532 nm
1620 nm
Parametric Amplifier
Spatial shaping via SLM
Spectral filter at 1620nm
DM
Monochro-mator
Lens
Lens
Single ring fibre in a gas chamber with Xenon
Lens
532 nm
SSPD
SM APD (zoom)
1620nm seed
Counts [Hz]
Wavelength [um]
2π
π
0
1.62

Future prospects

- Higher confinement
  - Smaller core
  - Higher overlap
  - Higher pressure ($\chi^{(3)}$)
- Alkali vapour + Xe
  - Higher $\chi^{(3)}$
  - Phase-matching between fundamental modes

R. B. Miles, and S. E. Harris, IEEE Journal of quantum Electronics (1973).

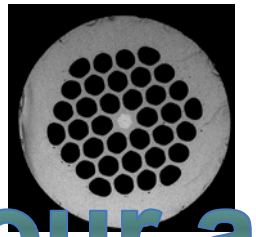
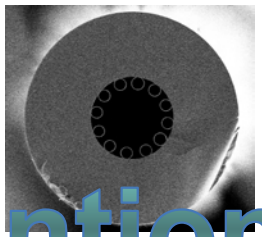
Summary

	Hybrid fibre	Single-ring fibre
Overlap integral	0.003 μm^{-2}	$8.4 \cdot 10^{-6}$ μm^{-2}
Nonlinearity	$6 \cdot 10^{-20}$ m^2/W	$4 \cdot 10^{-22}$ m^2/W
Phase matching	fixed	tuneable
Damage threshold	low	high
Length	limited by construction	limited by gas cell
Confinement losses	high for visible	high
Absorption losses	high above 1.6nm	very low

Conclusions

Hybrid | Single-ring

- Fibre designs:

Thank you for your attention!

- Third-harmonic generation:


- Photon triplet generation: