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Optoelectronics Research Centre

Tuneable multi-wavelength optical parametric amplification in multicore and multimode fibres

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Outline

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Optoelectronics Research Centre

- Introduction
- Background and Principles
- The use of Multimode & Multicore Fibres
- Recent results
- Conclusions

Introduction

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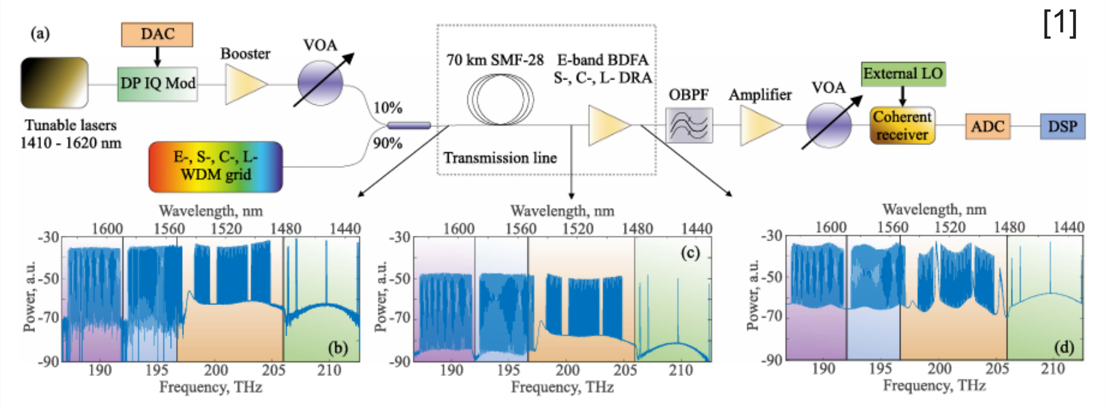
➢ Broadband multi-wavelength light sources

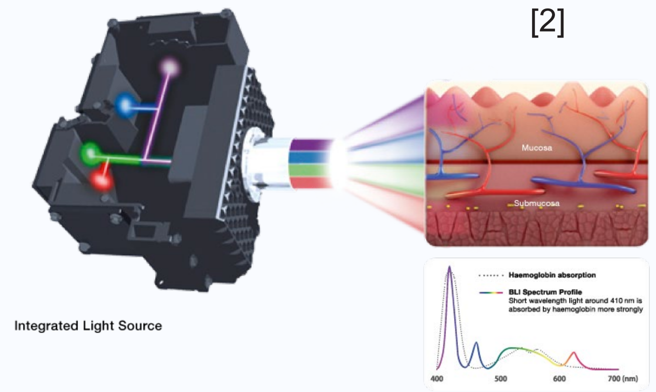
There has been an emerging need for laser light sources with new and improved capabilities.

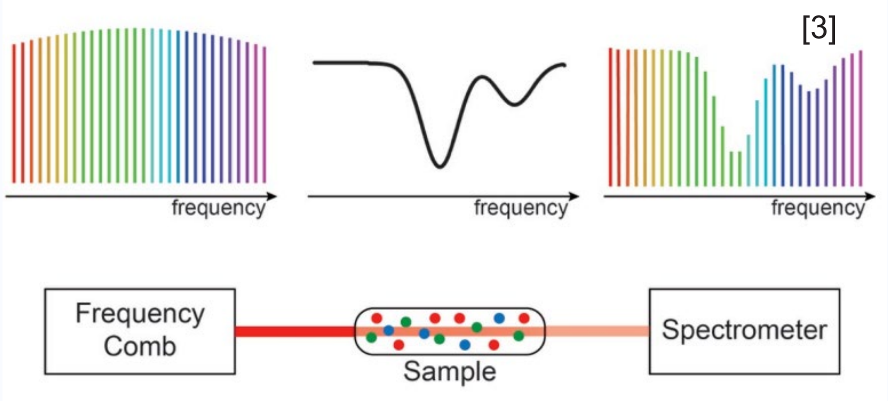
Broadband light sources are a popular and versatile option among the various types of light source.

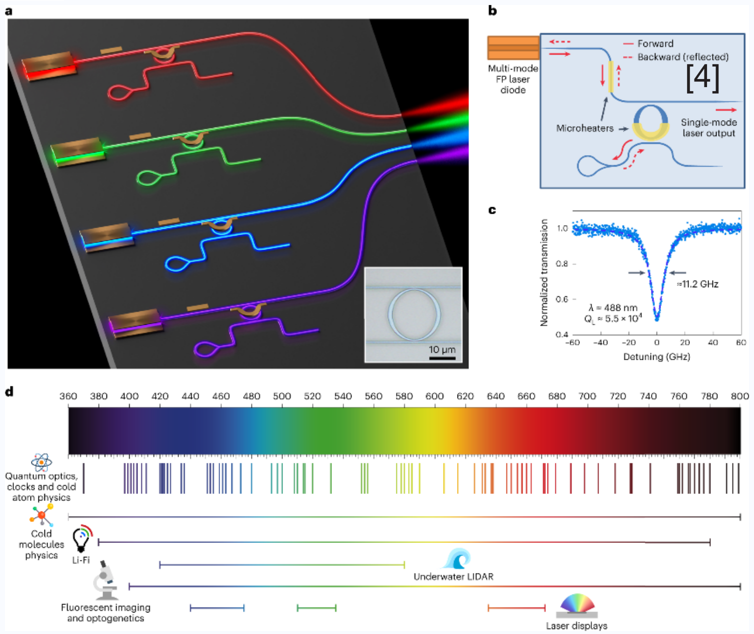
Real-world applications:

- Optical Communication
- Biomedical Imaging
- Spectroscopy
- Sensing & Monitoring
- Material Science & Metrology
- Addressing the needs of AI/ML
- …









[1] A. Donodin et al. Journal of Lightwave Technology, 42(7), 2024
[2] https://www.bli.eu/about-multi-light/
[3] N. Picqué et al. Nat. Photon. 13, 2019.
[4] M. Corato-Zanarella et al. Nat. Photon. 17, 2023.

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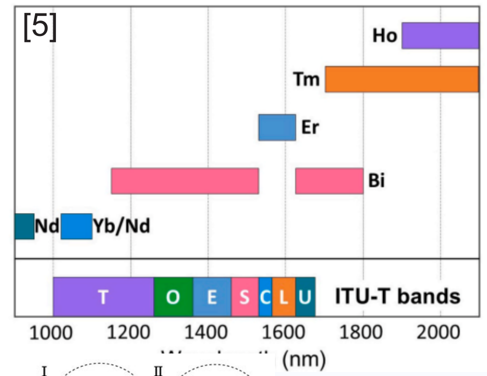
➢ Ways to achieve multi-wavelength emission

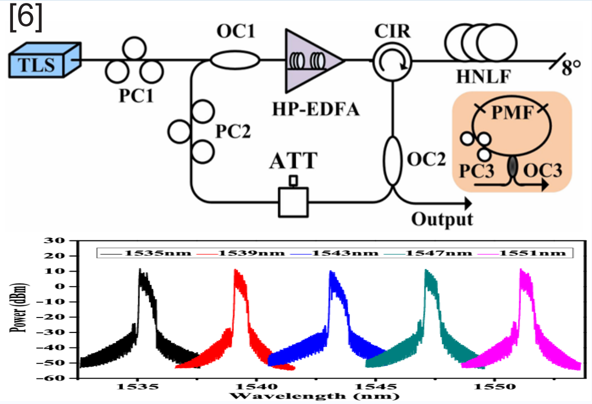
- **Linear**

Rare-earth-doped fibres

Wavelength-selective elements & cavity design:

Fabry-Perot filter, Mach-Zehner interferometer, Loop mirror, Lyot filter, fibre Bragg gratings,…





- **Nonlinear**

Stimulated Brillouin scattering (SBS)

Stimulated Raman scattering (SRS)

Four-Wave Mixing (FWM)

Second/Third Harmonic Generation

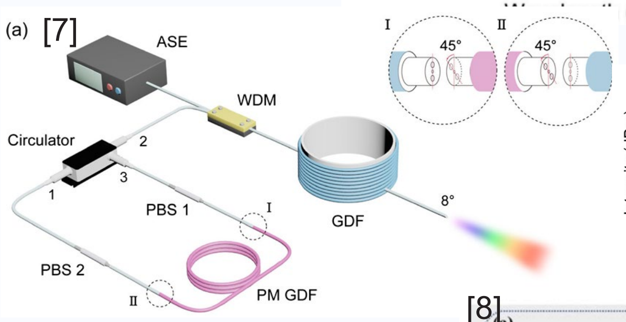
Supercontinuum Generation

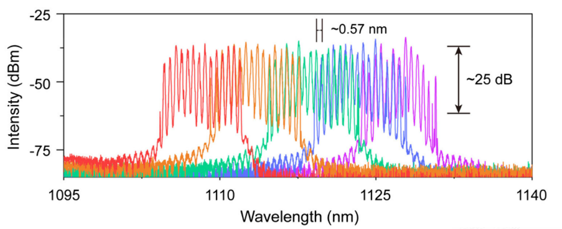
Random fibre laser (based on passive fibre) + spectral filtering

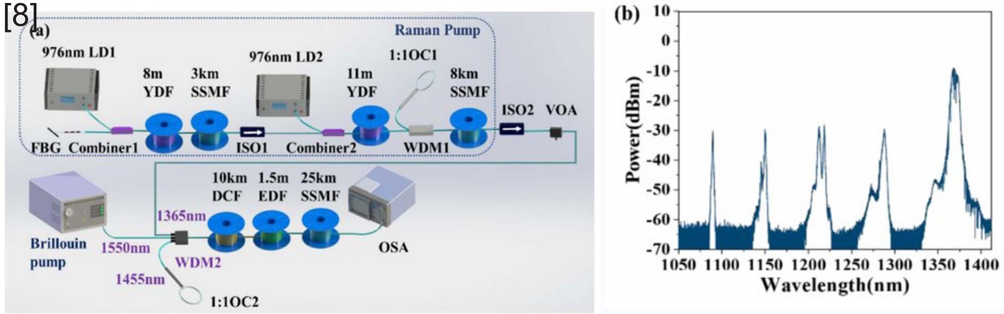
Optical Parametric Amplification (OPA)

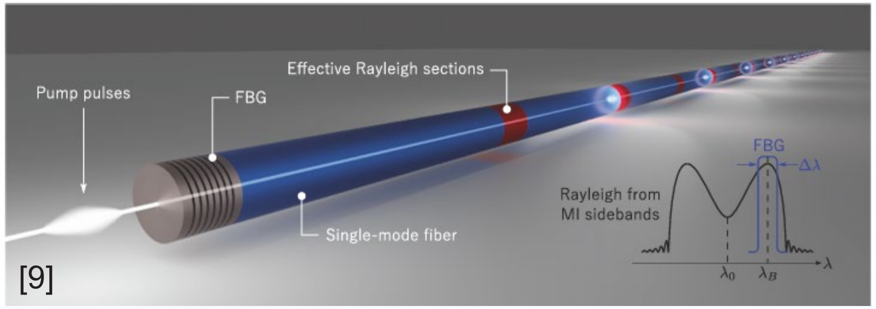
Optical Parametric Oscillation (OPO)

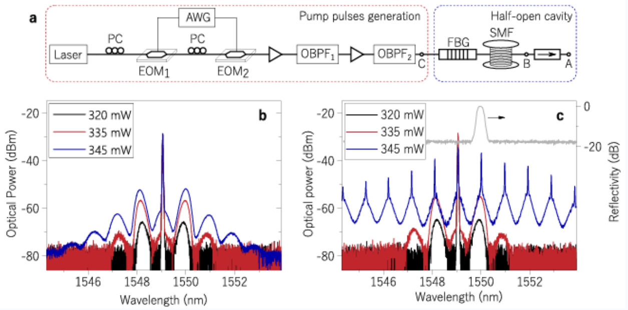
Random Optical Parametric Oscillator











[5] Y. Wang et al. Optical Materials: X 17, 2023
[6] F. Wang et al. Journal of Lightwave Technology 38(15), 2020.
[7] Y. Ye et al. Optics Letters 45(7), 2020.
[8] B. Han et al. Journal of Lightwave Technology 43(3), 2025.
[9] P. Tovar et al. Nature Communications 14, 2023

Introduction

➢ Ways to achieve multi-wavelength emission

- **Fibre/Waveguide design strategies**:

Multimode fibres (multiple sidebands across different modes)

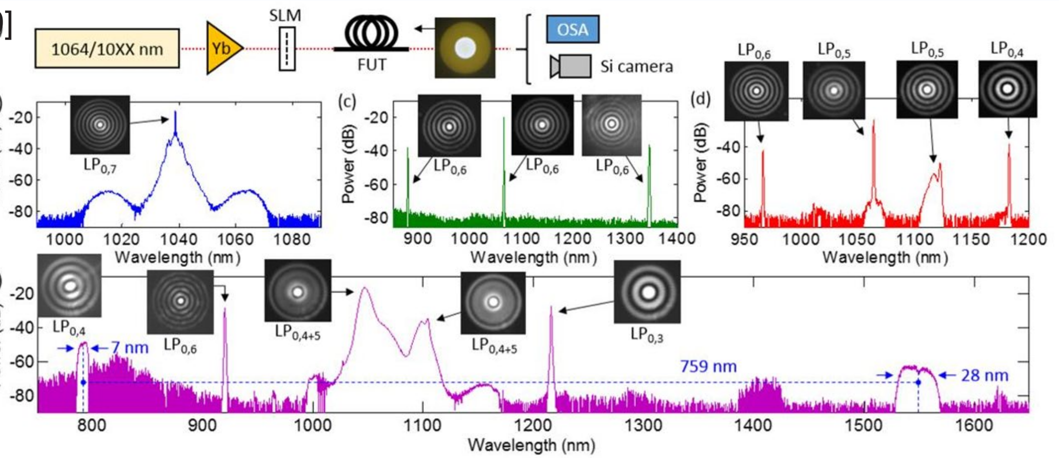
Photonics crystal fibres & Dispersion-engineered fibres

Multicore fibres & Microstructure fibres

Tapered fibres

Coupled waveguide

[10]



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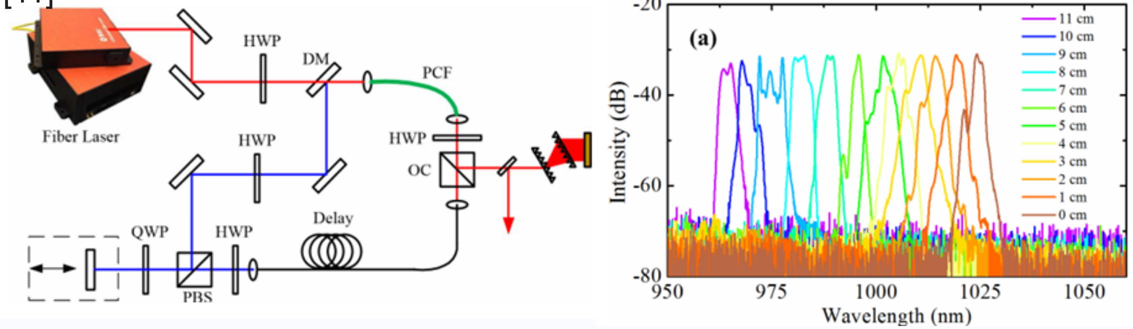

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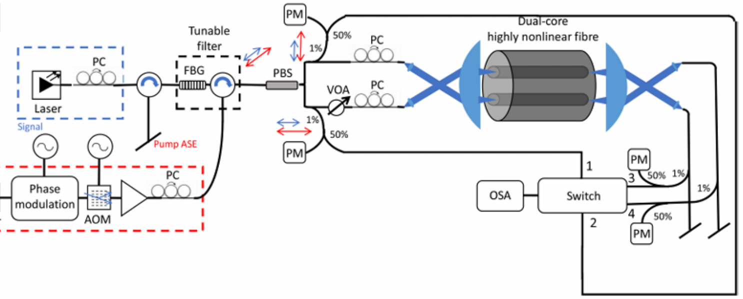

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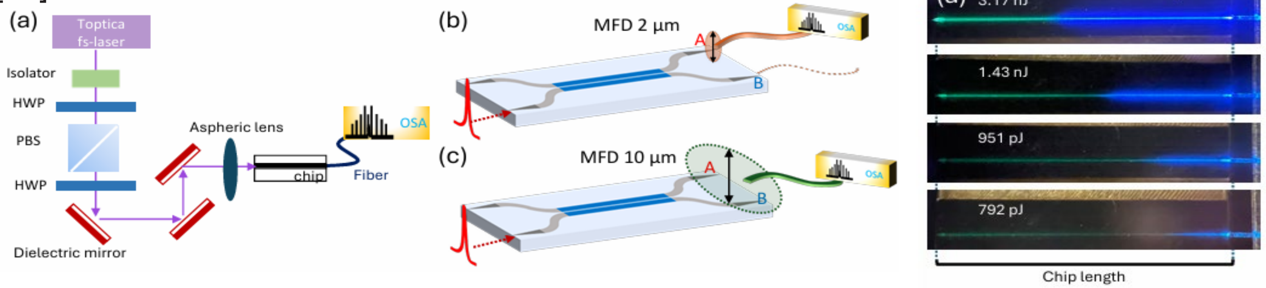

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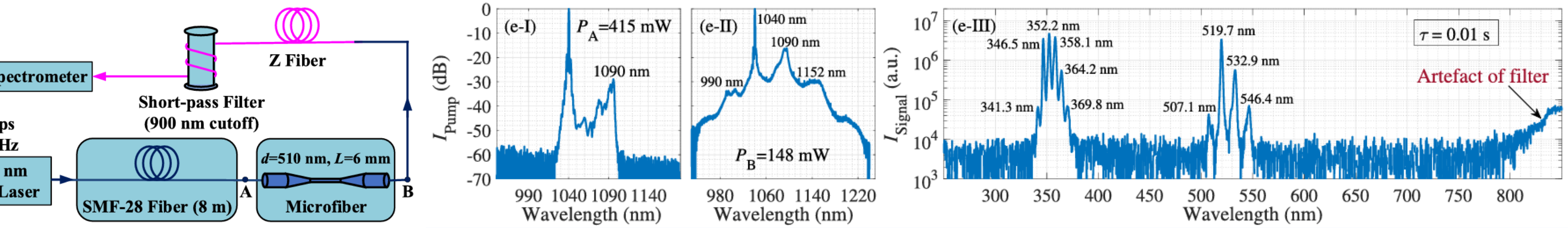
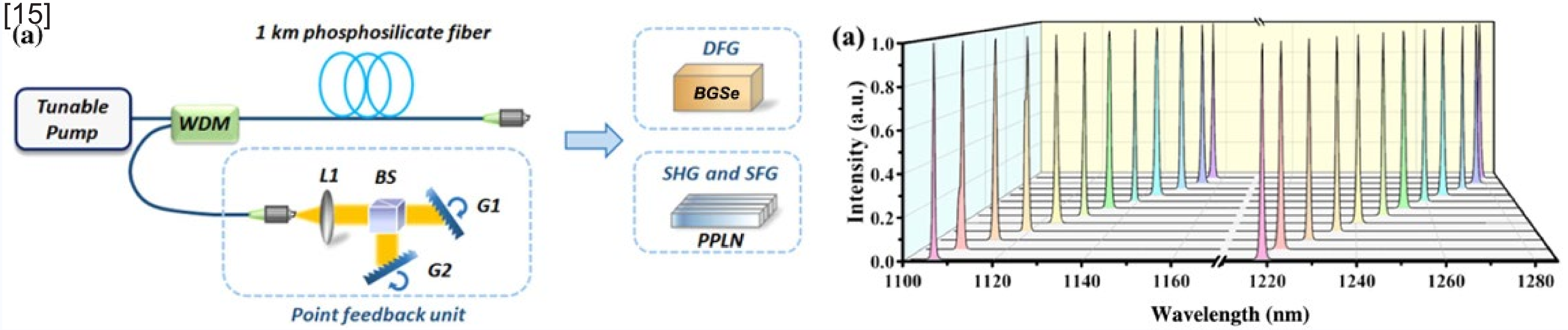


[10] J. Demas et al. CLEO SM3M.1 2017.
[11] K. Yang et al. IEEE Photonics Technology Letters 30(7) 2018.
[12] X. Jiang et al. Optics Letters 49(20) 2024.
[13] V. Ribeiro et al. Journal of Lightwave Technology 40(17) 2022.
[14] L. Xia et al. arXiv:2410.24073v2 2024.

➢ Ways to achieve tuneable multi-wavelength emission

- Tuneable pump (power, wavelength, rep rate)
- Tuneable spectral filter
- Electrical / Temperature control
- OPA
- OPO
- Choose from multiple modes

[15]



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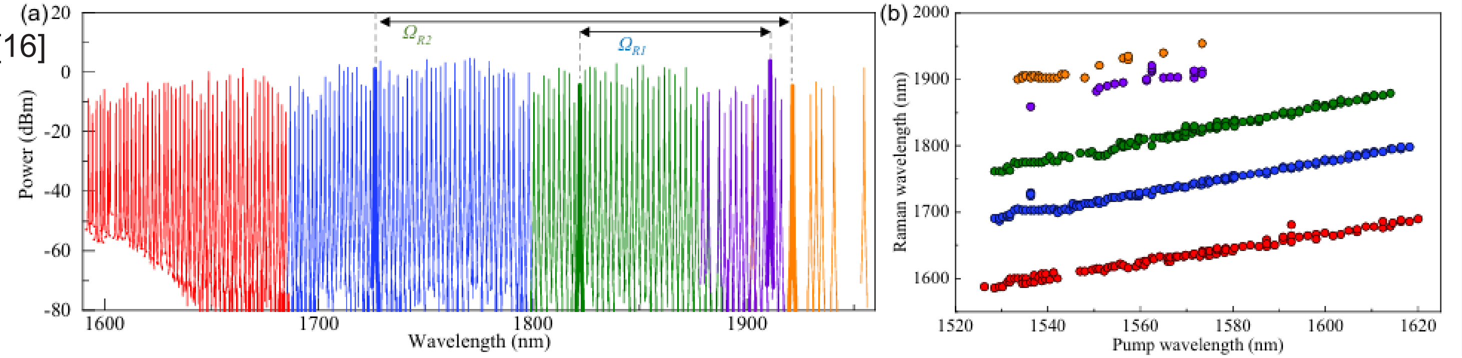

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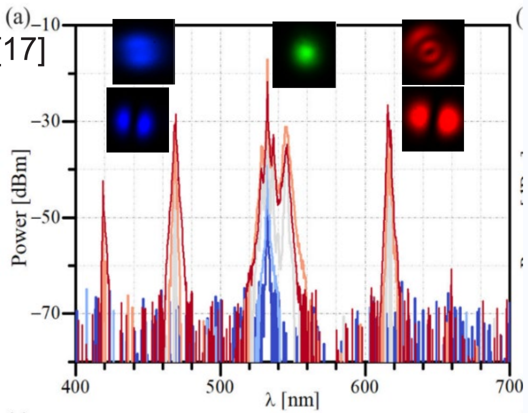

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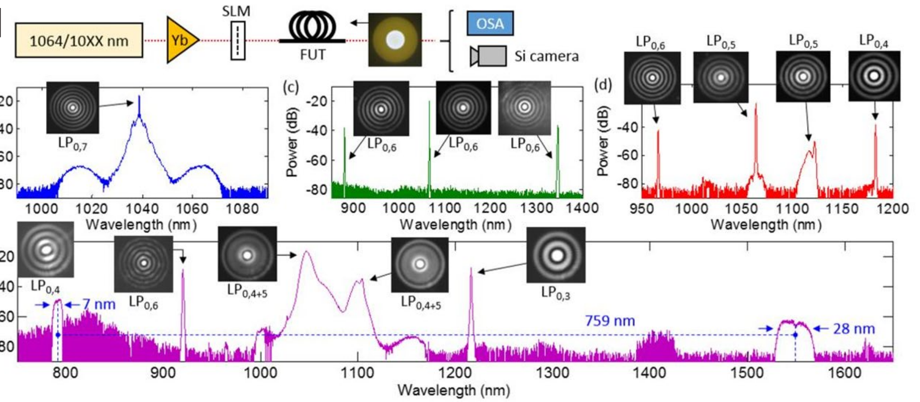
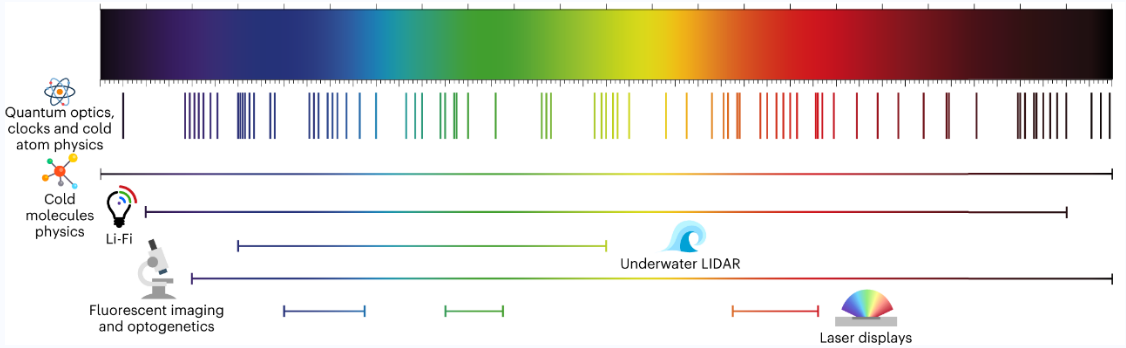
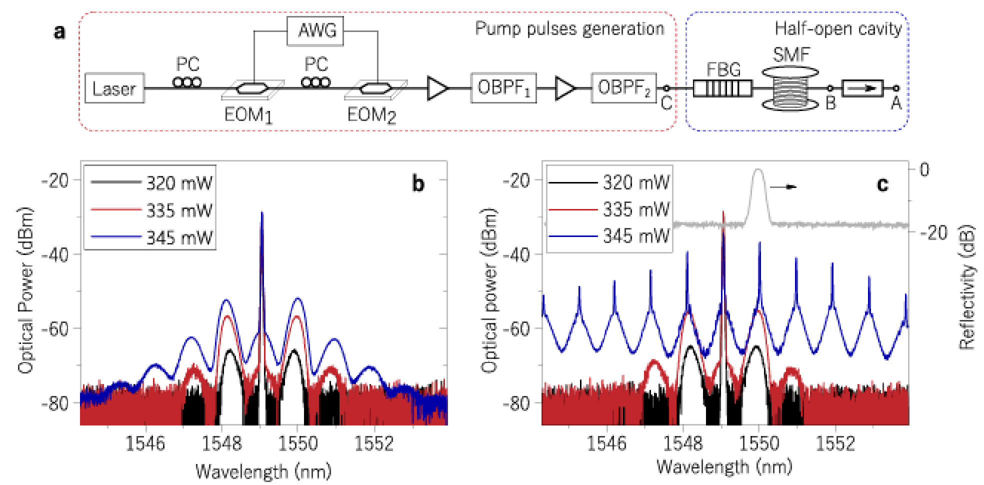


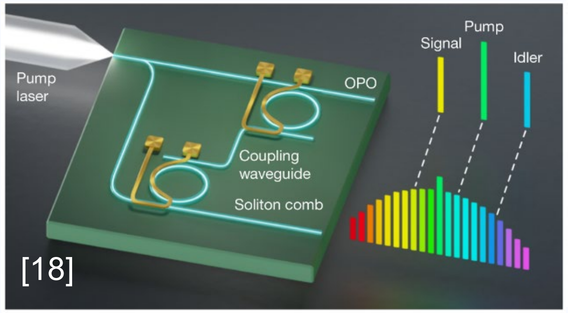
[10] J. Demas et al. CLEO SM3M.1 2017.
[15] H. Wu et al. Photonics Research 11(5) 2023.
[16] Y. Zhao et al. Communications physics 6:350 2023.
[17] Kwaśny, Michał, et al. Materials 15(13) 2022.

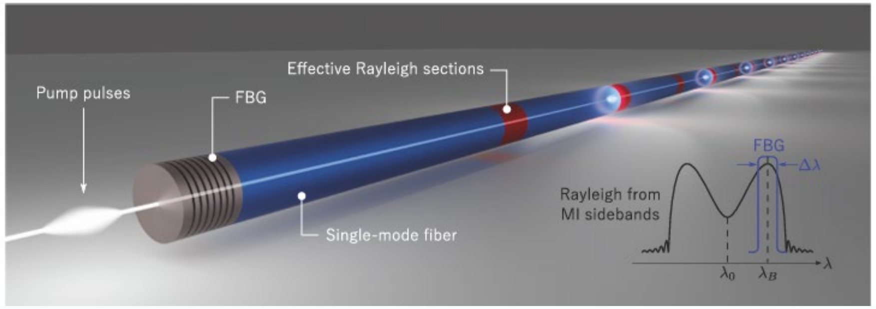
➢ Why OPA/OPO?

- Broad wavelength tuneability: covers UV to mid-IR
- Allowing narrow linewidth
- High coherence between the wavelengths
- Cascaded processes enable broad spectral range
- Can operate in CW, ns, ps, fs regimes
- Various platforms: chip-scale, fibre-integrated
- High peak power
- High conversion efficiency, low loss
- Polarization and Mode control









[18] Y. Zhao et al. Nature 627, 2024

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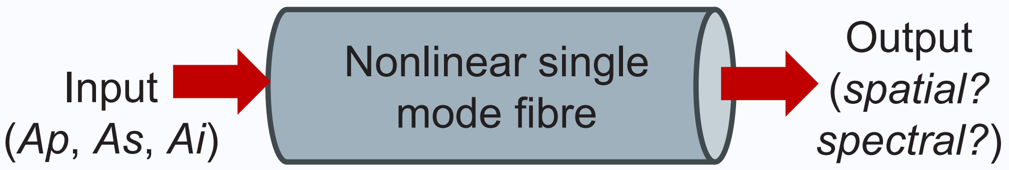
Background and Principles

➢ Basics of fibre OPA/OPO

Four-Wave Mixing in single mode fibres:

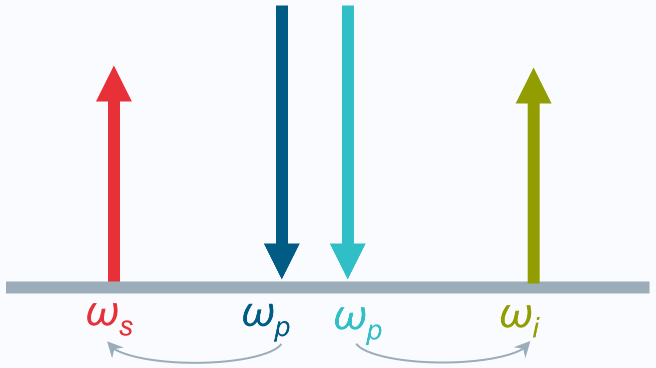


The propagation of a signal follows[15]:

$$\partial_z As = \overset{\text{Dispersion}}{\boxed{i\sum \frac{\beta_k}{k!}(i\partial_t)^k As}} + \overset{\text{Kerr nonlinearity}}{\boxed{i(1-f_R)M}} + \overset{\text{Raman}}{\boxed{f_R Rs}}$$

$$M = 2\gamma|Ap|^2 As + \gamma Ap^2\, Ai^*\, e^{i\left(\Delta\beta^{ps}+\Delta\beta^{pi}\right)z}$$

Intramodal four-wave mixing
Pumping at Near zero-dispersion wavelength



Generating new frequencies(ω_s/ω_i)

[15] Agrawal GP. Nonlinear Fiber Optics (Sixth Edition). Academic Press; 2019

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➢ Basics of fibre OPA/OPO

Four-Wave Mixing in multimode fibres:

The propagation of a signal in the n-th mode follows[15]:

$$\partial_z As_n = \overbrace{\boxed{i \sum \frac{\beta_k}{k!} (i\partial_t)^k As_n}}^{\text{Dispersion}} + \overbrace{\boxed{i(1 - f_R)M}}^{\text{Kerr nonlinearity}} + \overbrace{\boxed{f_R R s_n}}^{\text{Raman}}$$

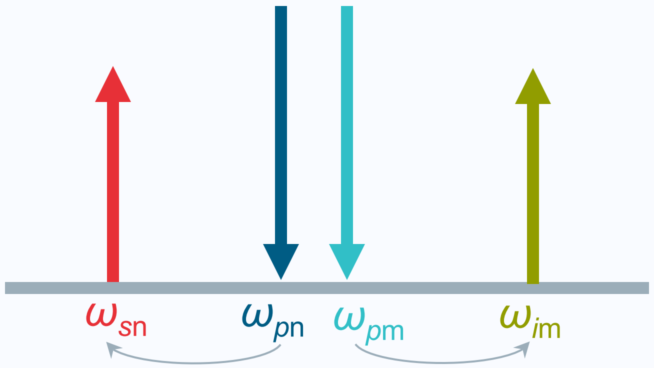
$$M = \sum_m 2\gamma_{nm} |Ap_m|^2 As_n + \sum_m 2\gamma_{nm} Ap_n Ap_m^* As_m e^{i(\Delta\beta_n^{ps} - \Delta\beta_m^{ps})z} + \underbrace{\gamma_{nn} Ap_n^2 Ai_n^* e^{i\left(\Delta\beta_n^{ps} + \Delta\beta_n^{pi}\right)z}}_{\text{Intramodal four-wave mixing}} + \sum_m \underbrace{2\gamma_{nm} Ap_n Ap_m Ai_m^* e^{i\left(\Delta\beta_n^{ps} + \Delta\beta_m^{pi}\right)z}}_{\text{Intermodal four-wave mixing}}$$

Intramodal four-wave mixing

Pumping at Near zero-dispersion wavelength

Intermodal four-wave mixing

Zero-dispersion requirement is relaxed



Generating new frequencies(ω_s/ω_i) with different spatial modes(m/n)

[15] Agrawal GP. Nonlinear Fiber Optics (Sixth Edition). Academic Press; 2019

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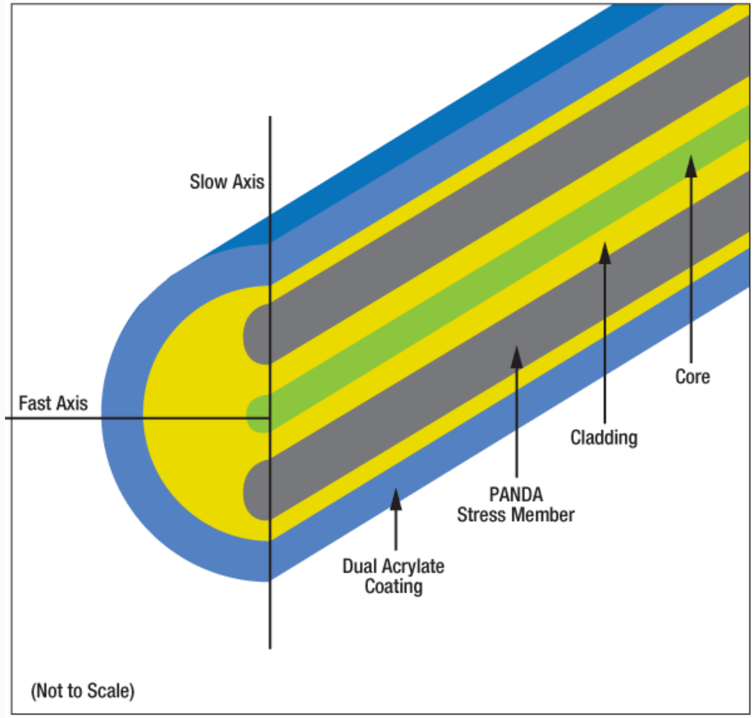
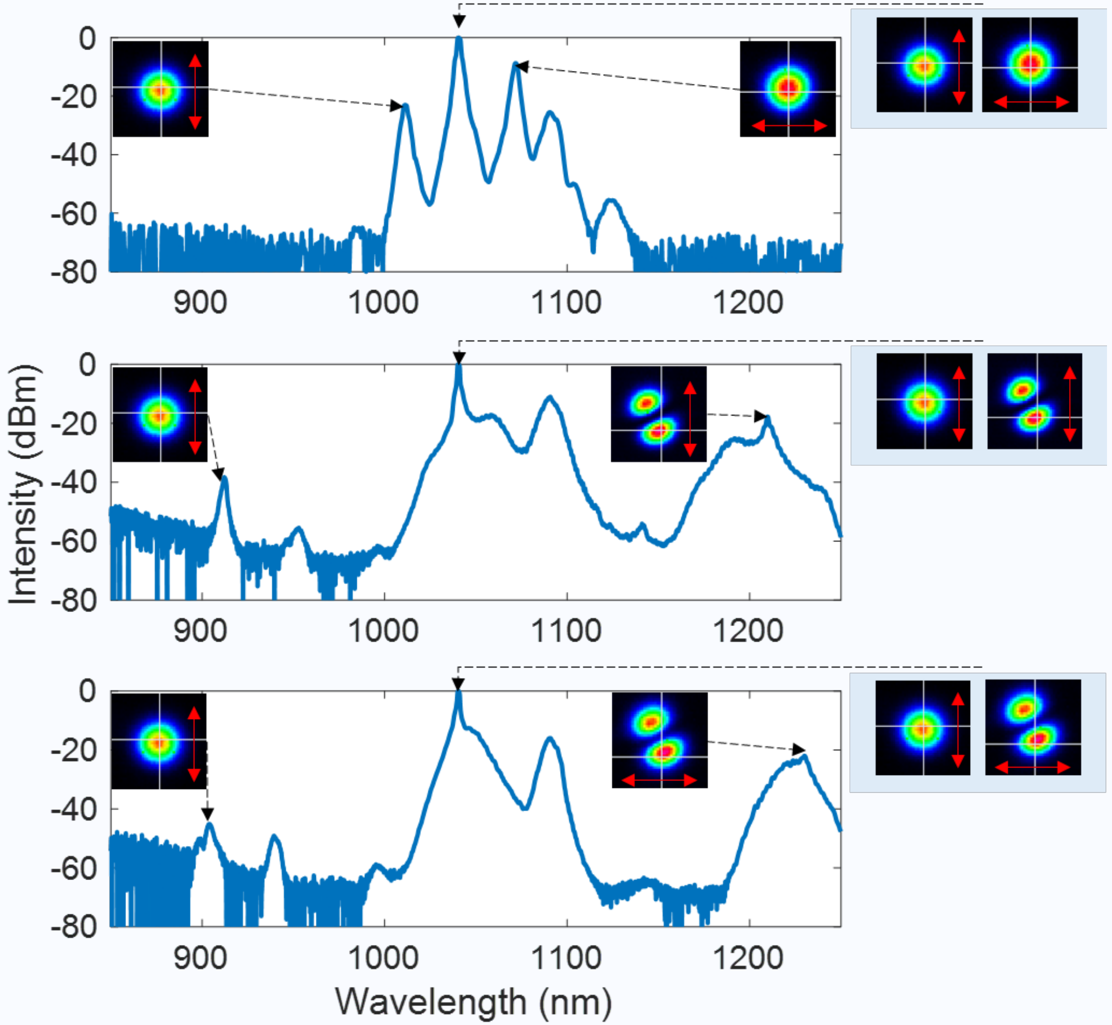
- Intermodal Four-Wave Mixing in MMFs



PM2000

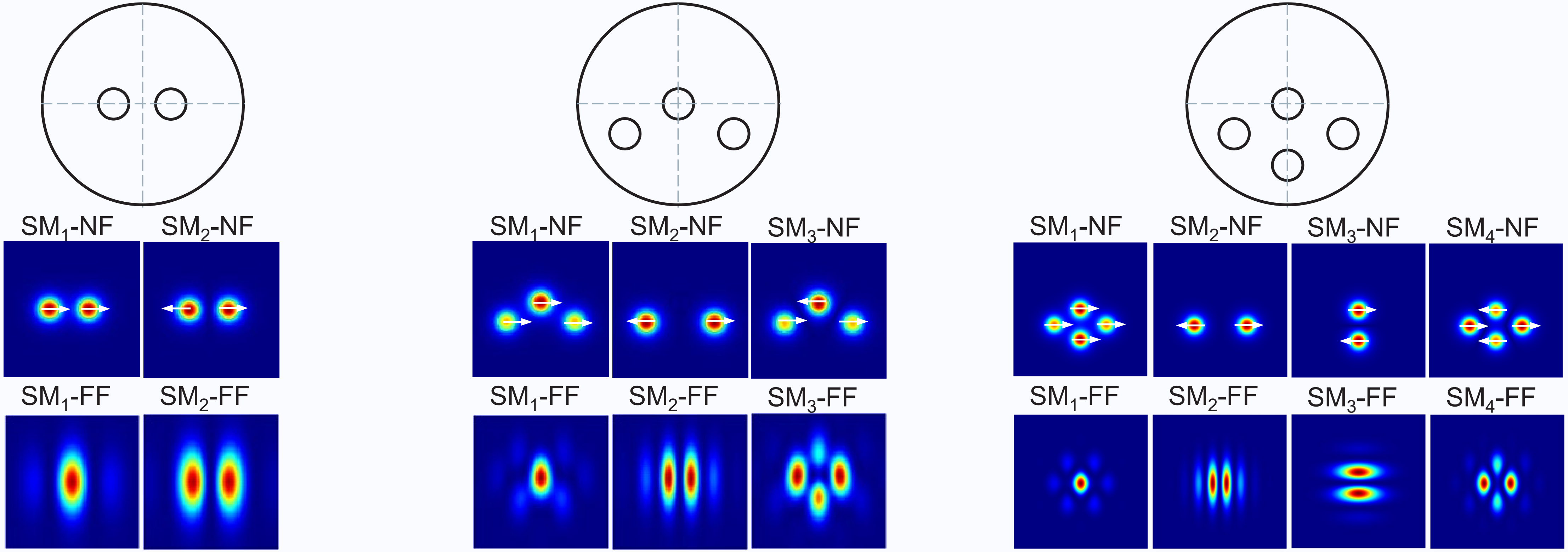


The use of MMFs and MCFs

- **An alternative mode choice for MCFs**: treat all cores as a whole → multimode structure

Forward Signal
(FS: F_1, F_2, …)

Intermodal FWM between different supermodes:
Phase matching conditions in various fibre designs



The use of MMFs and MCFs

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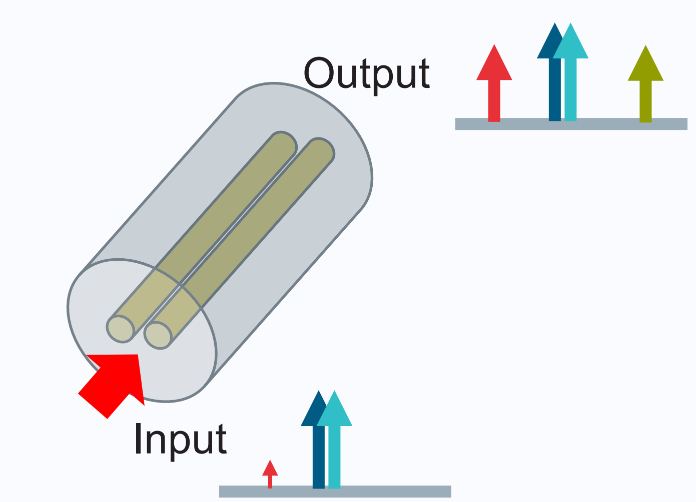
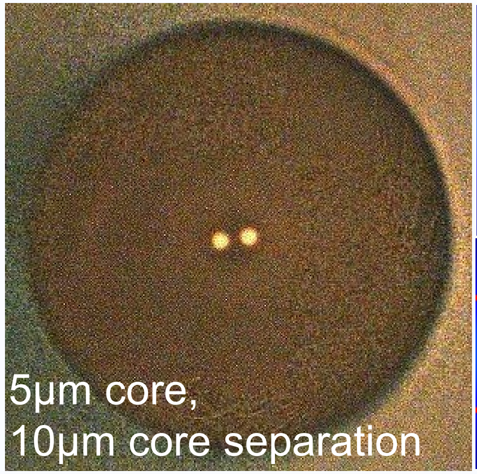
- Phase matching in MCFs

treat all cores as a whole→multimode structure

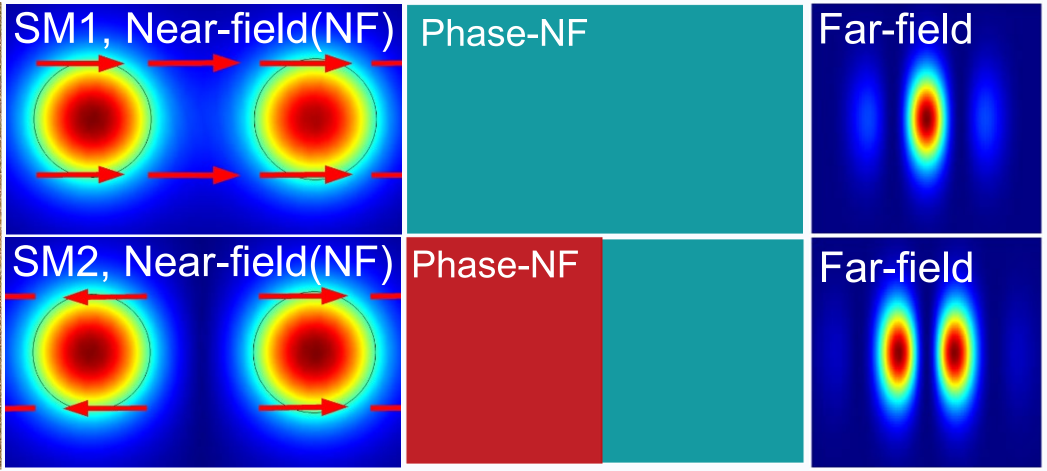
Platform: coupled multicore fiber

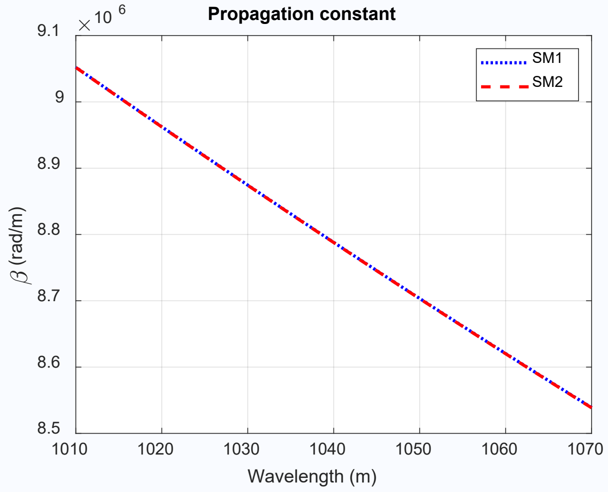


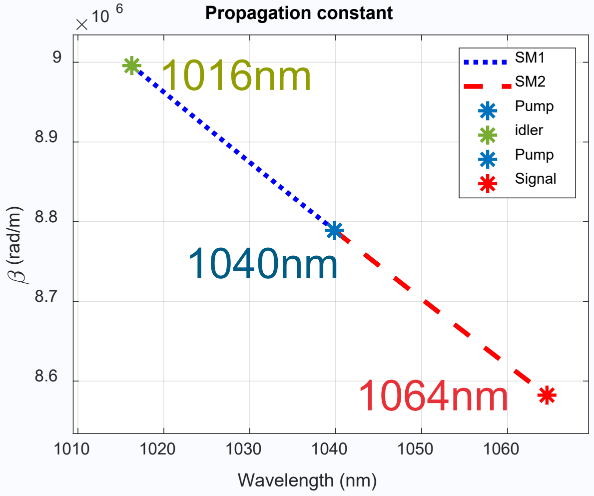
Cross section

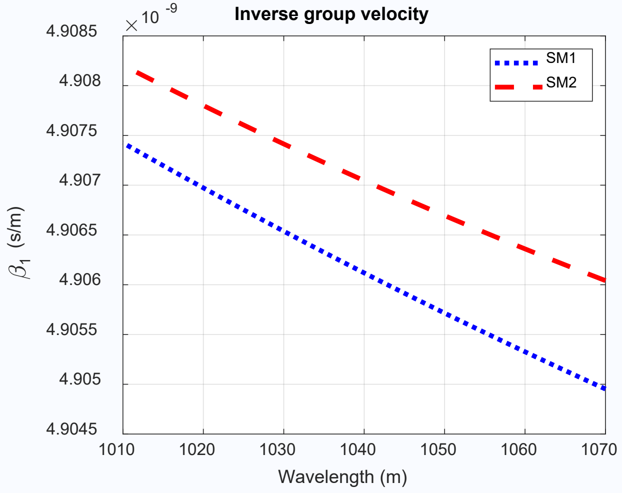


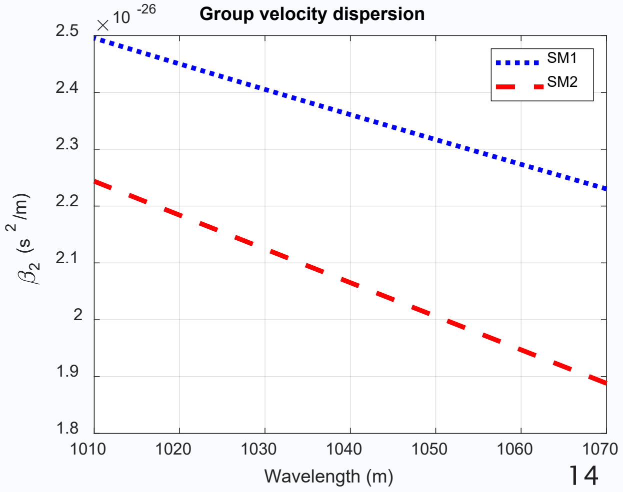
Transverse modes(Supermodes, SM)



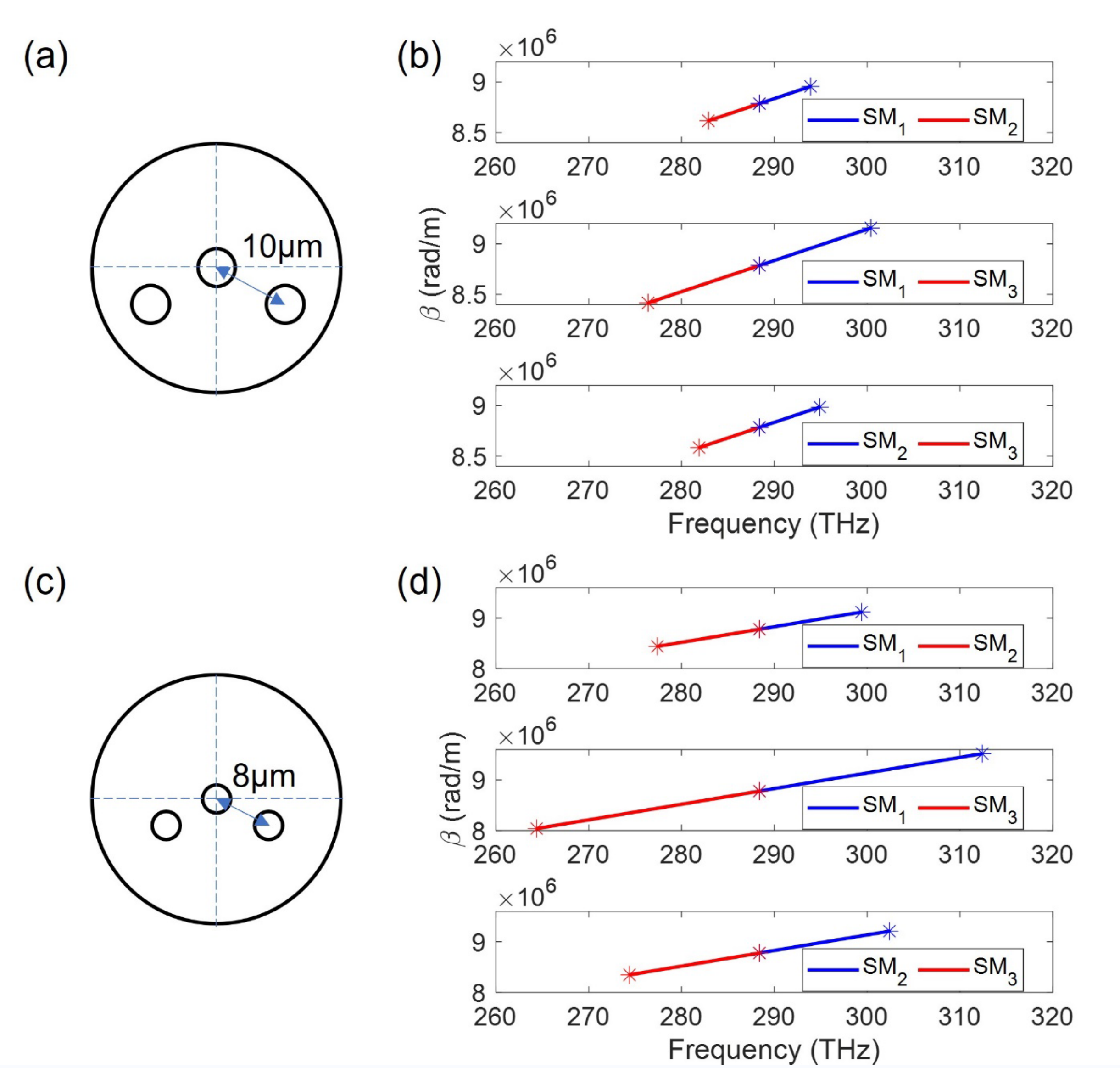




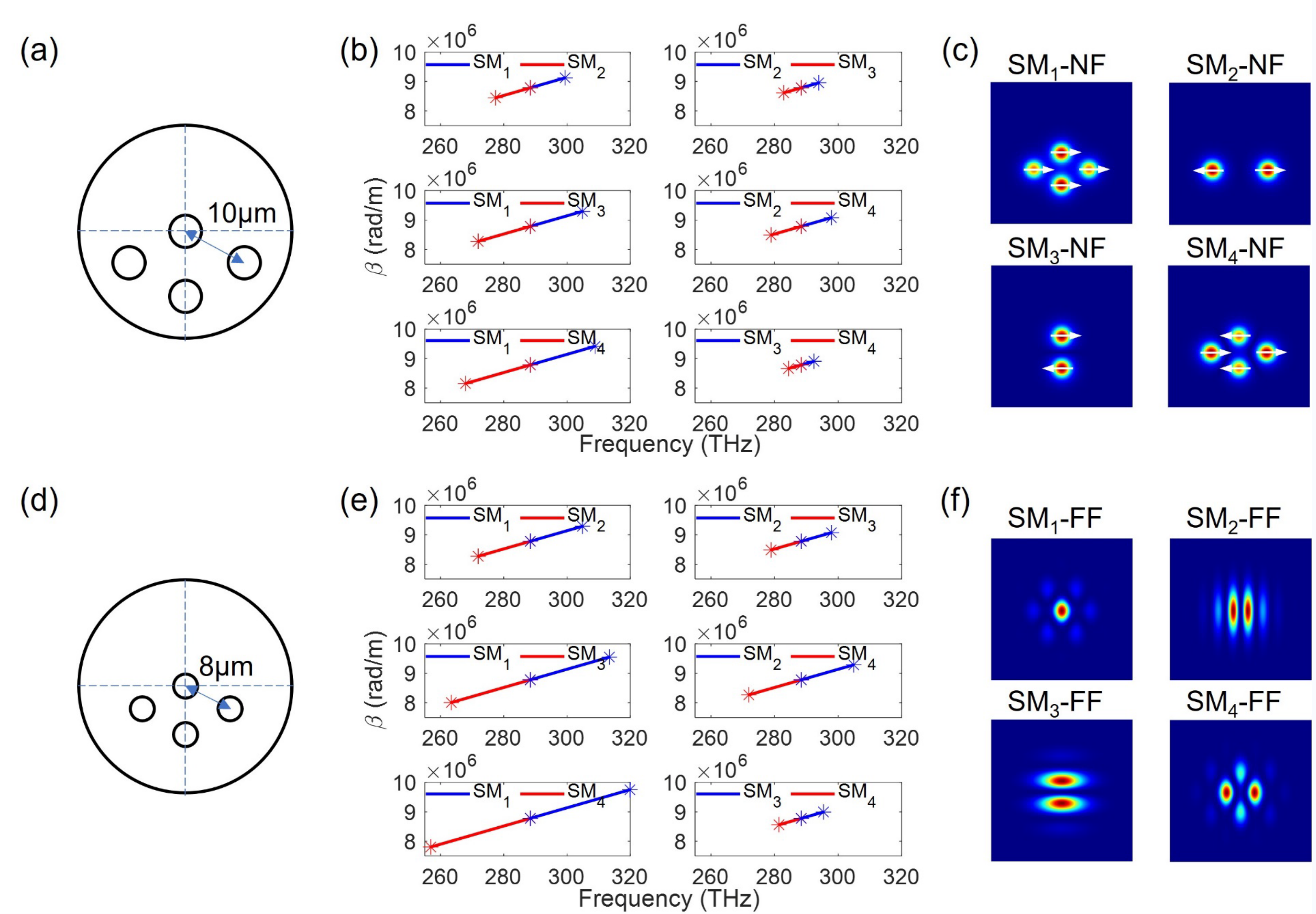




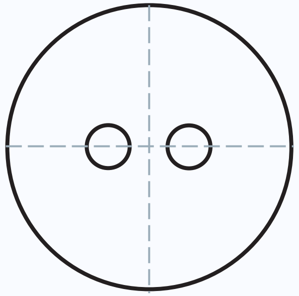
- Phase matching in MCFs

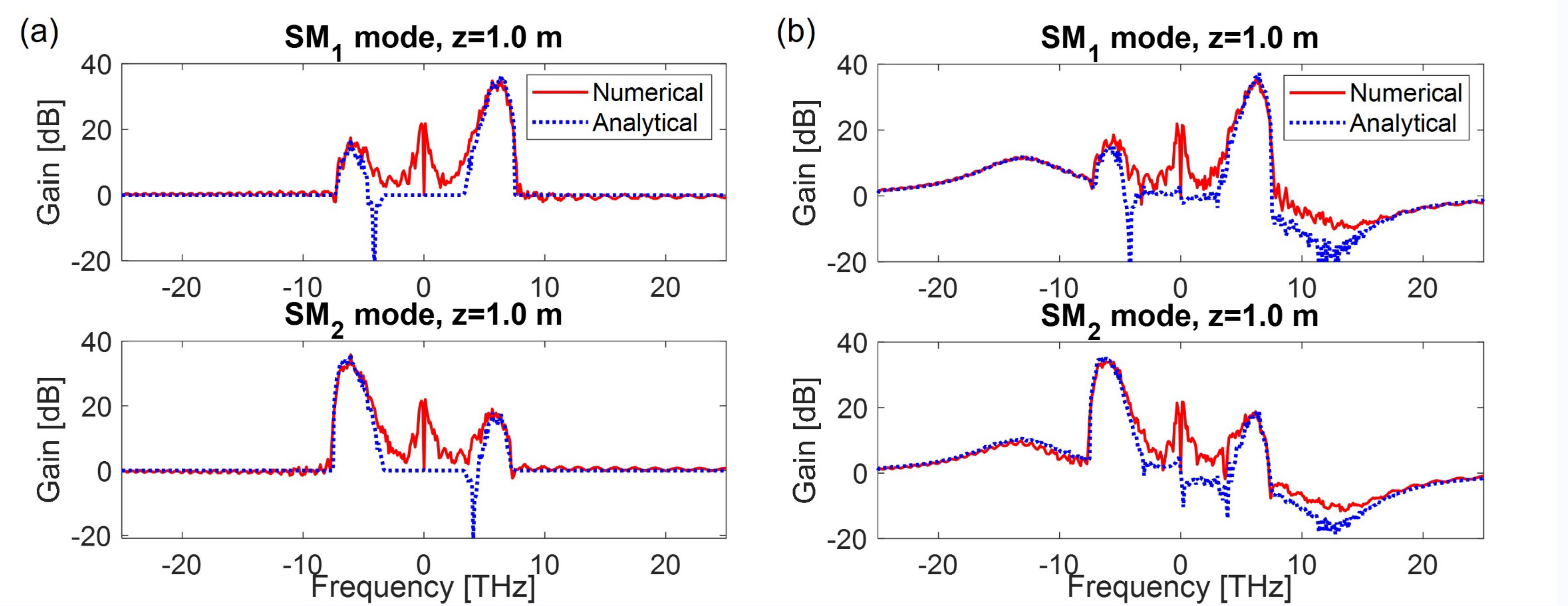


- Phase matching in MCFs



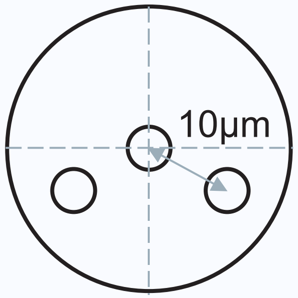
- OPA-MCFs

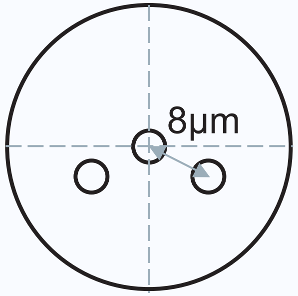


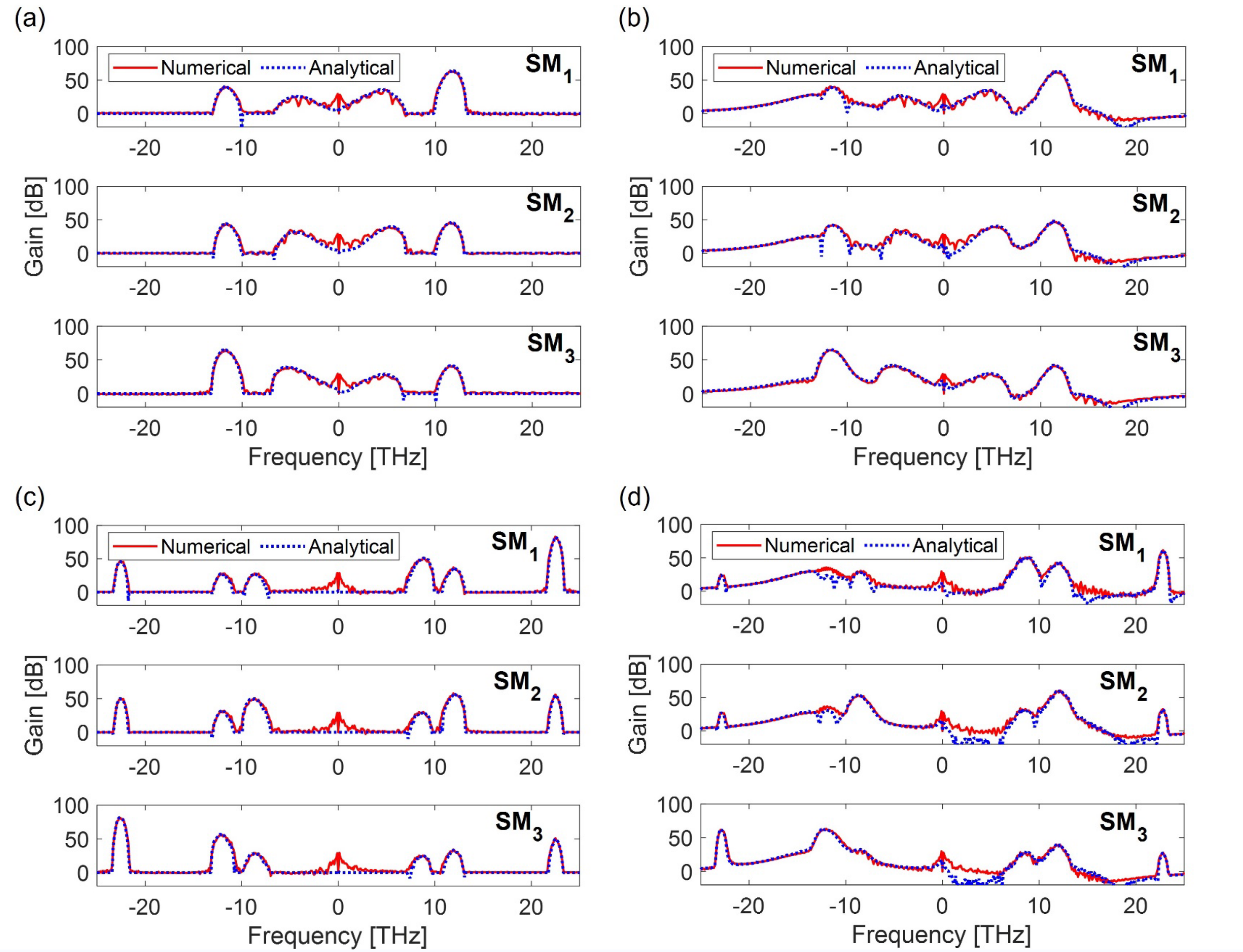

(a)
SM1 mode, z=1.0 m
SM2 mode, z=1.0 m
Numerical
Analytical
Gain [dB]
Frequency [THz]
(b)
SM1 mode, z=1.0 m
SM2 mode, z=1.0 m
Numerical
Analytical
Gain [dB]
Frequency [THz]

The use of MMFs and MCFs

- OPA-MCFs

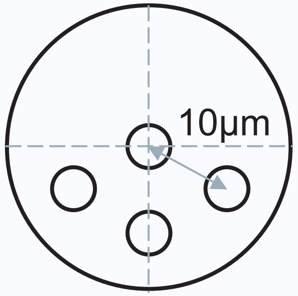


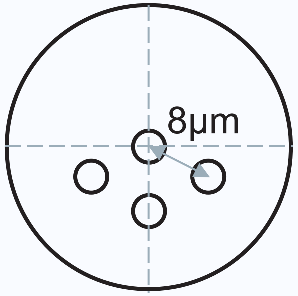


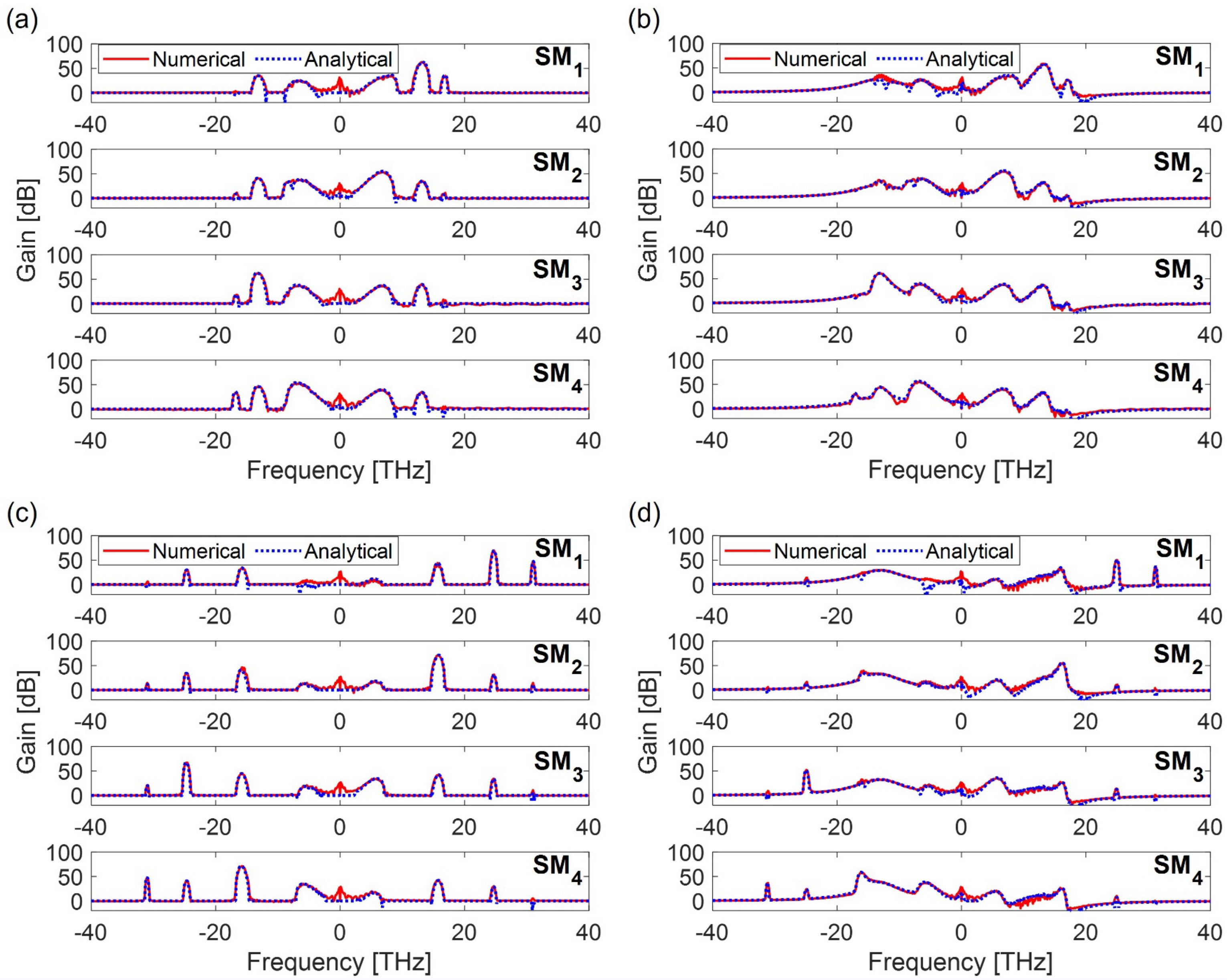


The use of MMFs and MCFs

- OPA-MCFs







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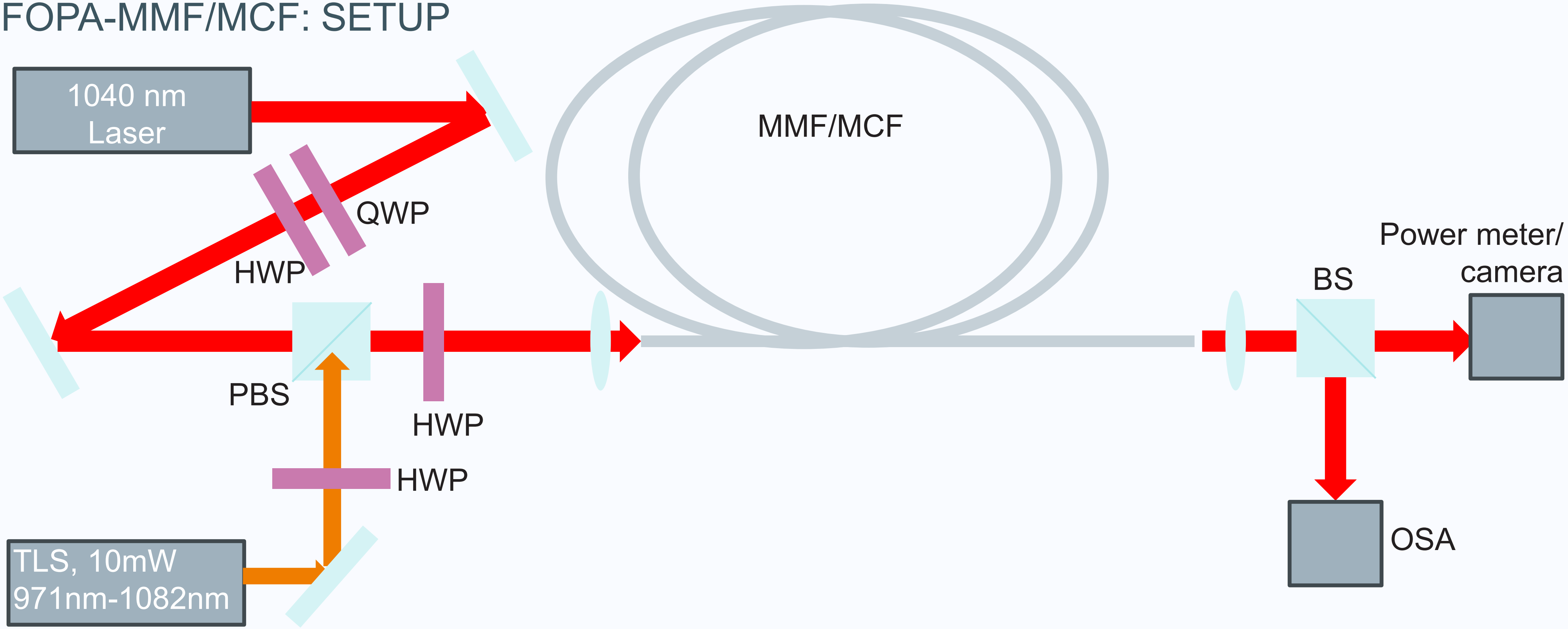
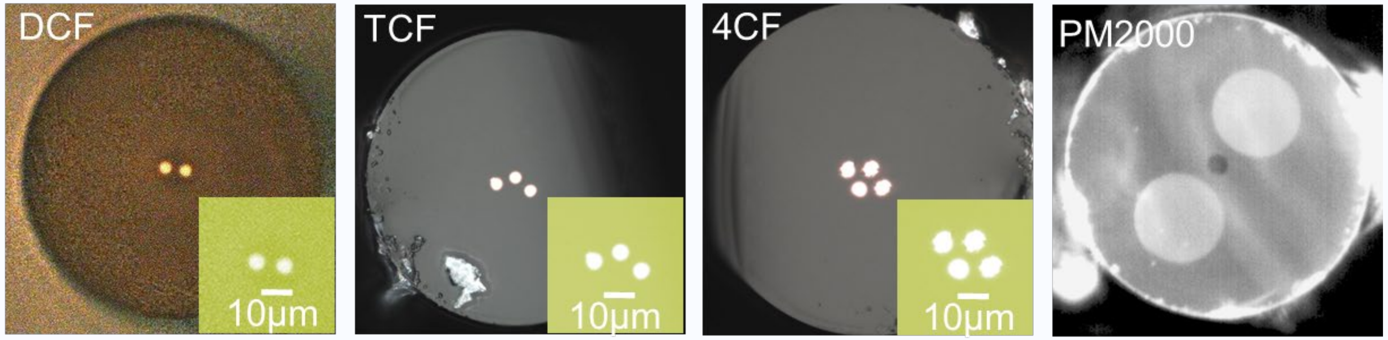
➢ FOPA-MMF/MCF: SETUP





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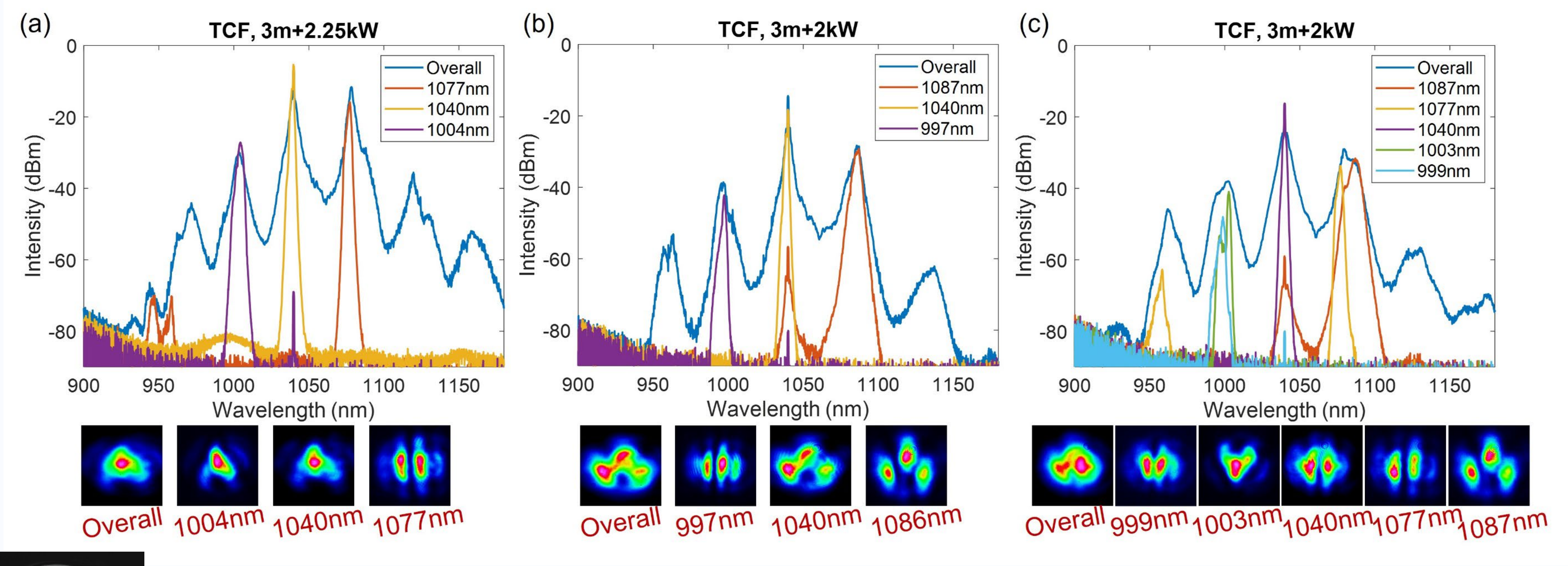
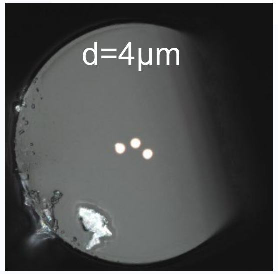
➢ CASE 1: FOPA-TCF





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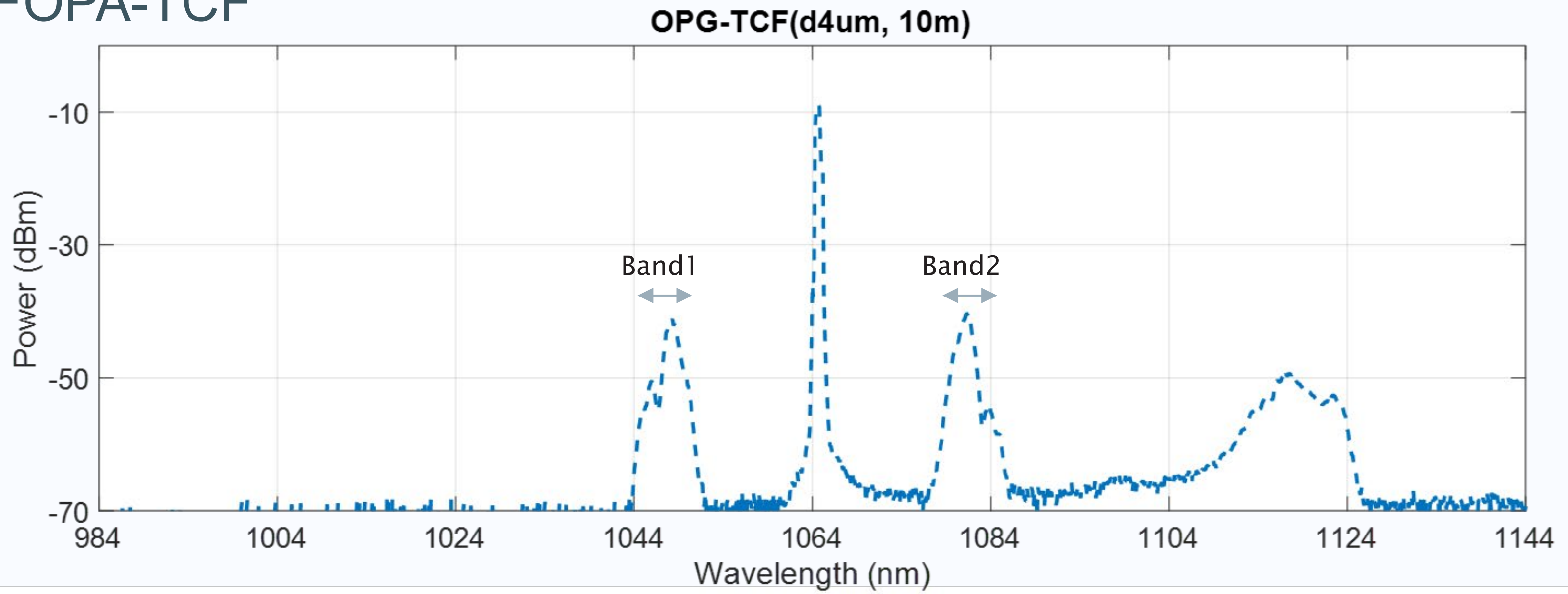
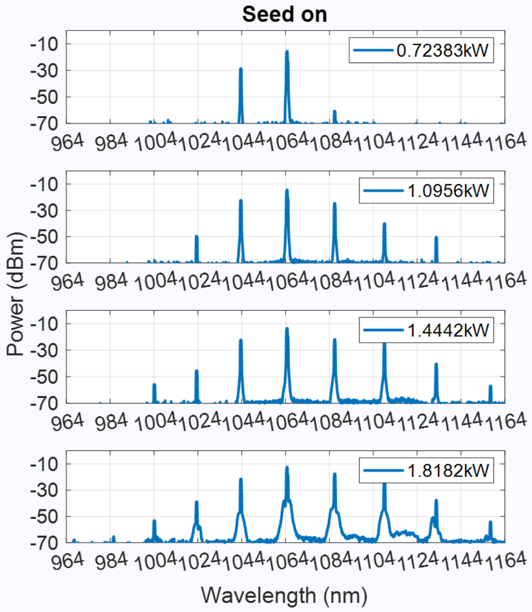
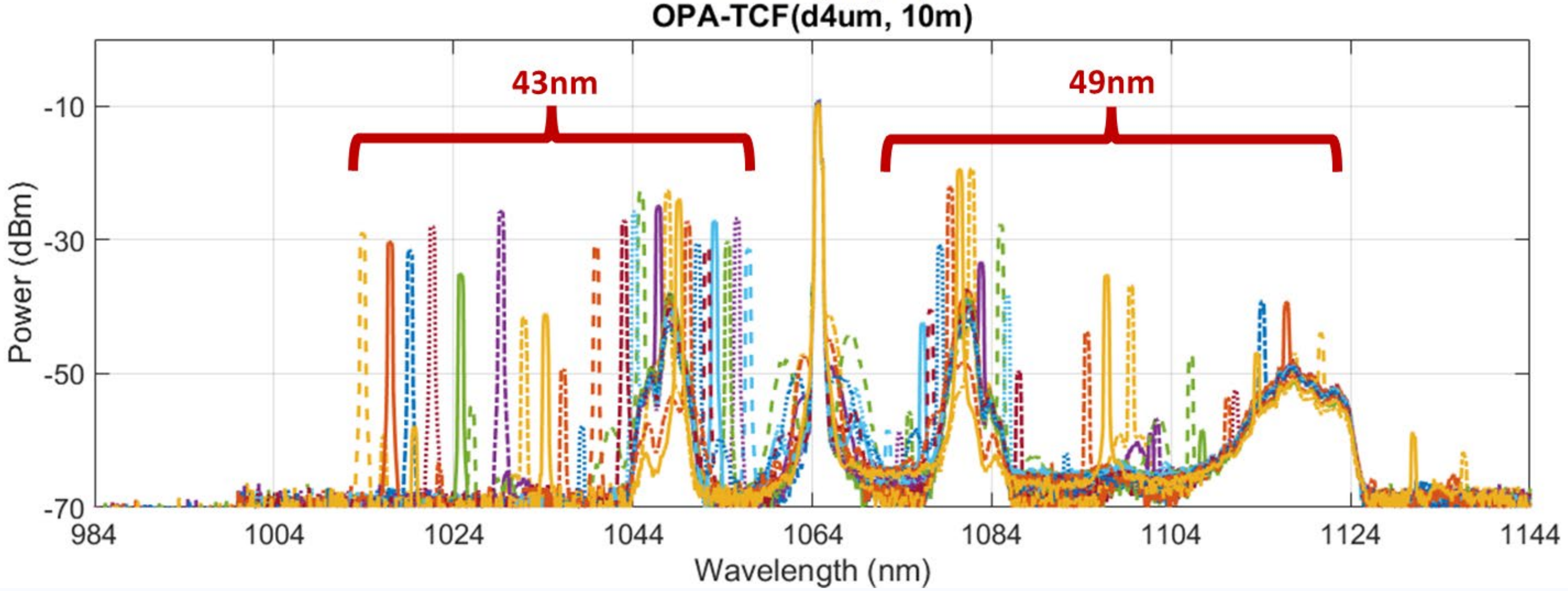
➢ FOPA-TCF







RESULTS

- Band1,2: 1047-1050 nm ; 1078-1081 nm
- Overall bandwidth: 1.6 THz
- WDM gain @pump 100mW: >10 dB
- WDM gain @pump 1 W: >17 dB

FOPA

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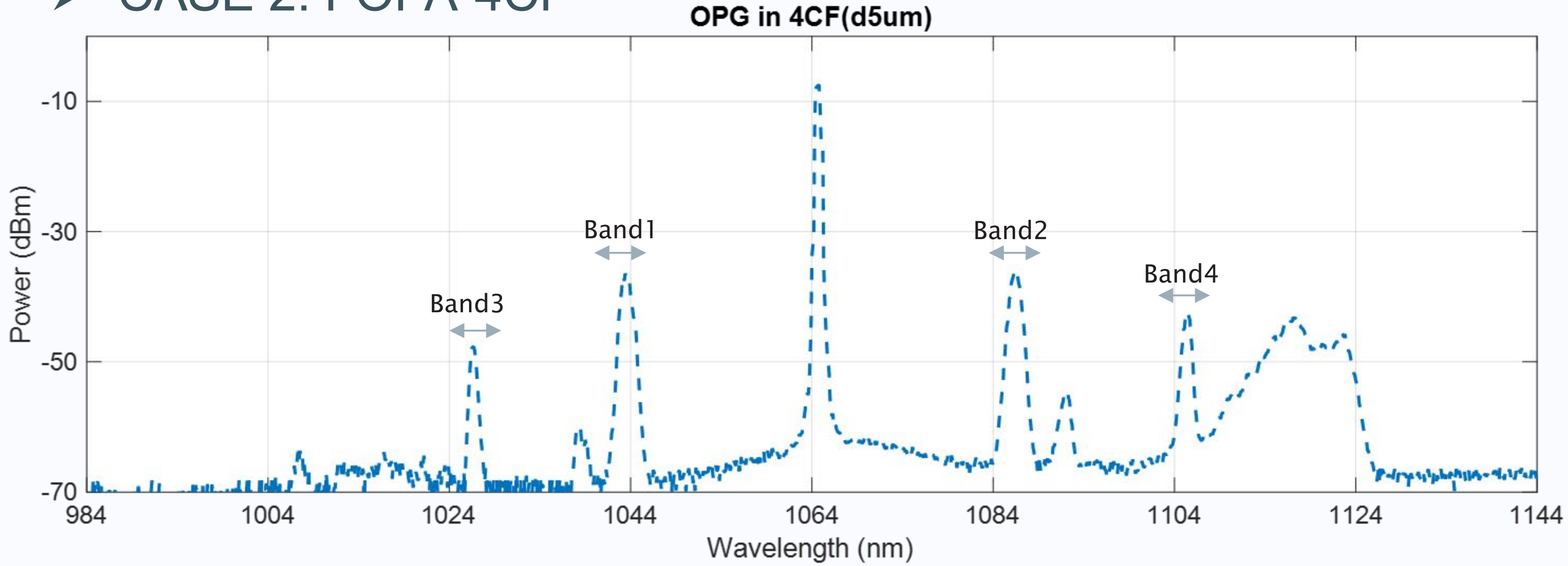
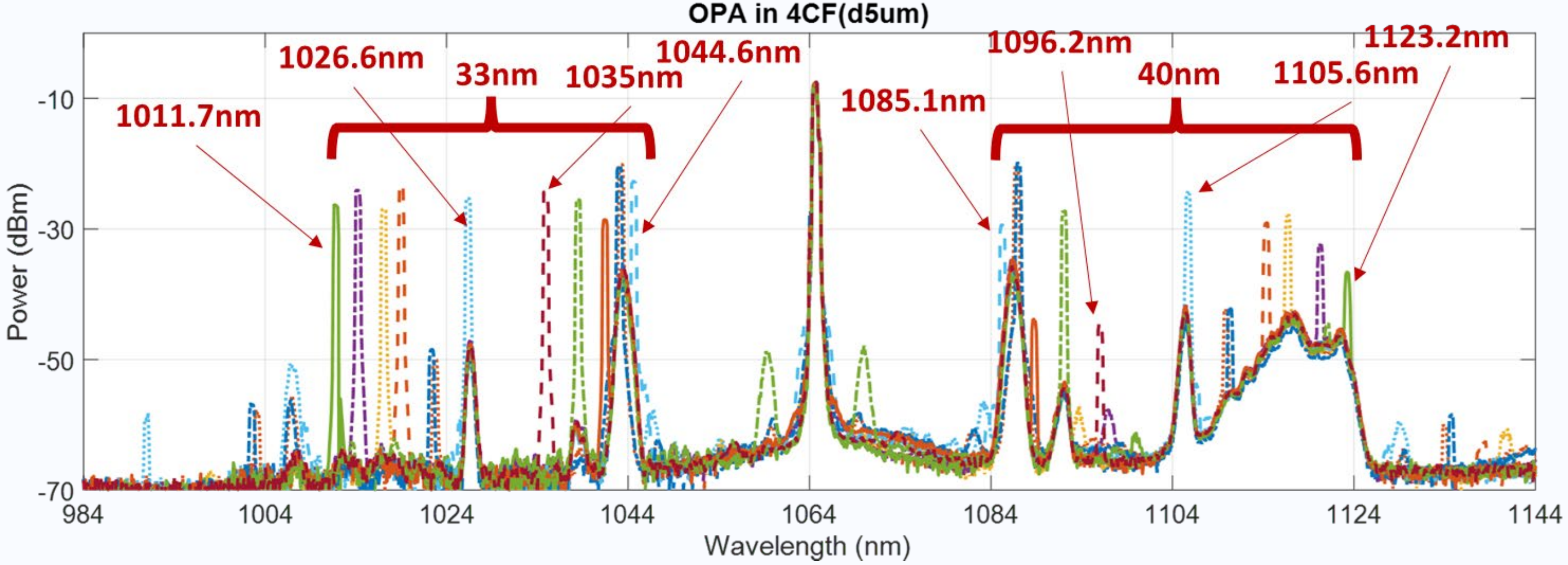
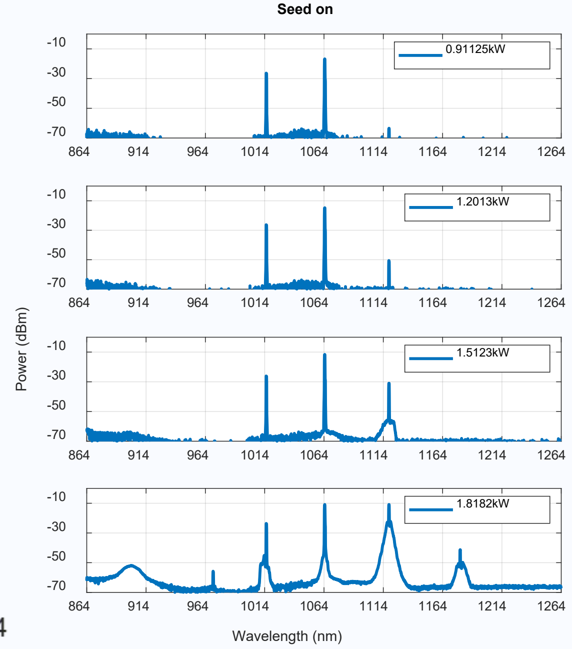
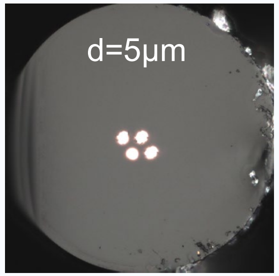
➢ CASE 2: FOPA-4CF









RESULTS

- Now 4 bands engineered via core-to-core pitch and core dimension
- Overall bandwidth: 3 THz
- WDM gain @pump 100mW: >8 dB (for proper pump mode composition)
- WDM gain @pump 1 W: >15 dB

- FOPA-MCF

Fibre		Relative frequency (THz) and the corresponding modes for FWM peaks with a pump wavelength of 1040 nm	
		Simulation	Experiment
DCF		±6.2 (SM_1 and SM_2)	±6.5 (SM_1 and SM_2)
TCF	core spacing=10 μm	±4.7 (SM_1 and SM_2), ±5.7 (SM_2 and SM_3), ±11.8 (SM_1 and SM_3)	
TCF	core spacing=8μ m	±10.3 (SM_1 and SM_2), ±13.9 (SM_2 and SM_3), ±24.3 (SM_1 and SM_3)	±10 (SM_1 and SM_2), ±12.5 (SM_2 and SM_3),
4CF	Core spacing=10 μm	±3 (SM_3 and SM_4), ±9 (SM_2 and SM_4), ±10.2 (SM_1 and SM_2), ±15.9 (SM_1 and SM_3), ±20.2 (SM_1 and SM_4)	±8, -11.5, -13
4CF	Core spacing=8μ m	±6.4 (SM_3 and SM_4), ±16 (SM_1 and SM_2), ±16.2 (SM_2 and SM_4), ±25.2 (SM_1 and SM_3), ±31.9 (SM_1 and SM_4)	±6.7 (SM_3 and SM_4), ±12.7, ±16.1, ±25.2, ±26.3

Fibre		Relative frequency (THz) and the corresponding modes for FWM peaks with a pump wavelength of 1064 nm	
		Simulation	Experiment
DCF		±7.5 (SM_1 and SM_2)	±7.6 (SM_1 and SM_2)
TCF	core spacing=10μ m	±5.8 (SM_1 and SM_2), ±7.2 (SM_2 and SM_3), ±14.2 (SM_1 and SM_3)	±5.7 ±12.5 ±13.3 (SM_2 and SM_3),
TCF	core spacing=8μm	±11.3 (SM_1 and SM_2), ±14.1 (SM_2 and SM_3), ±25.3 (SM_1 and SM_3)	±4.9 (SM_1 and SM_3), ±11.4 (SM_1 and SM_3), ±12.7 (SM_1 and SM_2),
4CF	Core spacing=10μ m	±3.8 (SM_3 and SM_4), ±10.9 (SM_2 and SM_4), ±11.9 (SM_1 and SM_2), ±18.6 (SM_1 and SM_3), ±23.8 (SM_1 and SM_4)	±5.7 (SM_1 and SM_2), ±7.1, ±10.2, ±13.6,
4CF	Core spacing=8μm	±6.4 (SM_3 and SM_4), ±16.5 (SM_2 and SM_4), ±17.3 (SM_1 and SM_2), ±26.7 (SM_1 and SM_3), ±33.2 (SM_1 and SM_4)	-6.2 ±8.5 (Mix or SM_2 and SM_4), ±19.6 (Mix and SM_4), ±29 (SM_1 and SM_4), -58.2

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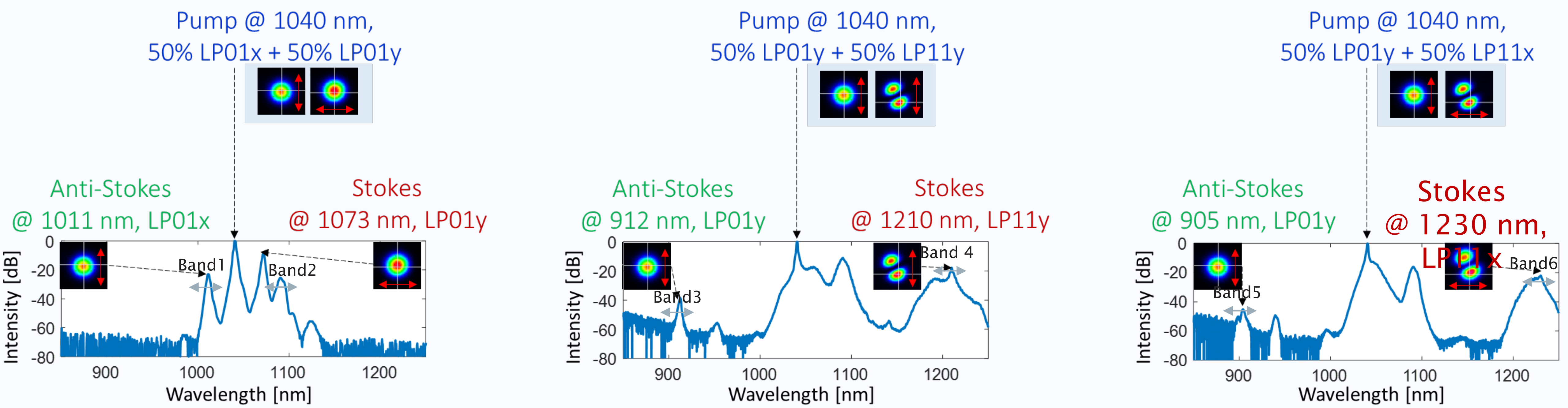
➢ CASE 3: FOPA-THREE-MODE-FIBER (PM2000 THORLABS)



RESULTS

- 6 bands far from the pump (Band 1 to 6: 1009-1012nm; 1071-1074nm; 910-913 nm; 1208-1213 nm; 904-906 nm; 1229-1233 nm)
- Overall bandwidth: ~ 5 THz (more than the entire C-band)
- WDM gain @pump 1 W: >14 dB in all bands for proper pump mode distribution
- Estimated WDM gain @pump 10 W (simulations doubling fiber length): >27 dB in all bands for proper pump mode distribution

Important! Band 1,3,5: the amplified mode is the fundamental one (y-polarized)
Towards elastic networks

Conclusions

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➢ Four-wave mixing in MCFs / MMFs:

- FWM between supermodes / LP modes
- Raman / Raman+FWM in MCFs
- Supermode + wavelength conversion and amplification in 2-core/3-core/4-core fibres
- Mode + wavelength conversion and amplification in PM2000 fibre

➢ Results:

- Multicore fibres: multiple amplification/conversion bands are engineered via core size and core-to-core pitch
- Amplification band can be far away from the pump **(>50 THz in our fibres**)
- In PM 2000: 6 bands, overall bandwidth ~ 5 THz **(more than the entire C-band!)**
- WDM gain @pump 1 W: >14 dB in all bands (estimated gain > 27 dB for 10-W pump power, if doubling the fiber length)
- The bands can be activated individually or simultaneously adjusting the pump modal composition
- We can generate a wide spectral region for single-mode amplification: towards elastic networks