# Designing multicore fibers for high-power fiber amplifiers

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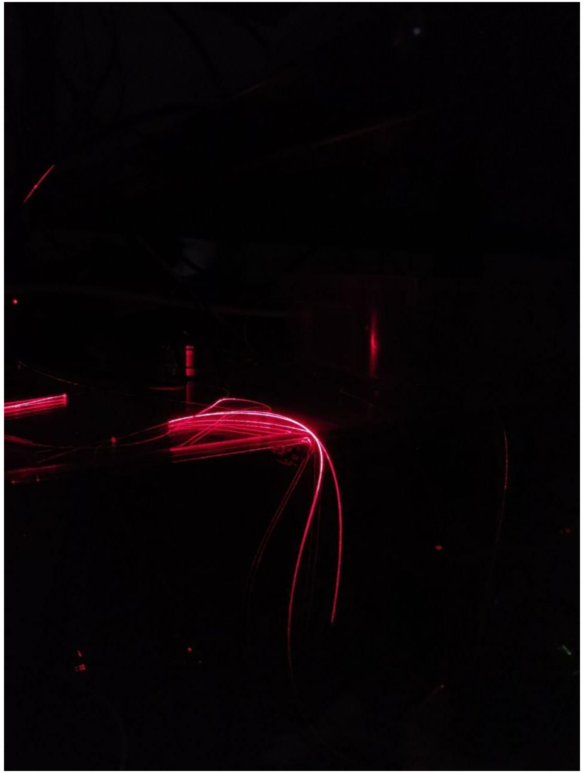
# Outline

- Optical fibers
- Fiber modes
- Fiber lasers
- Spatial nonlinear effects
- Experiments with multicore fibers
- Coherent combining

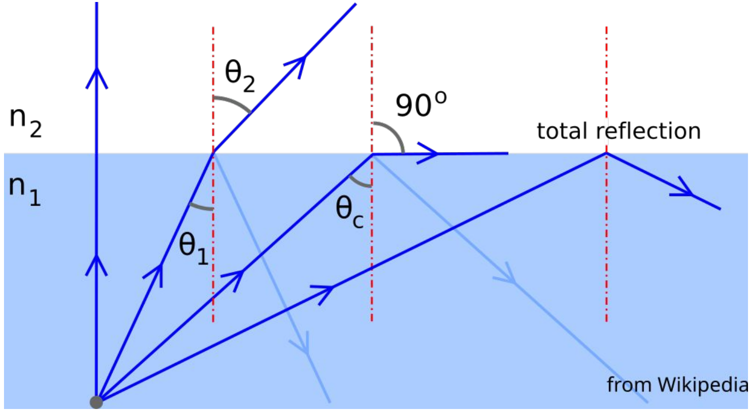


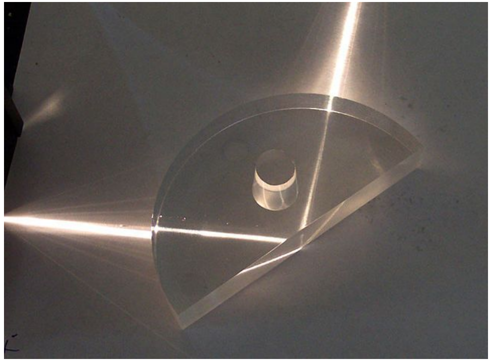
# Total internal reflection

- On the interface of two media, light refracts according to the Snell's law

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

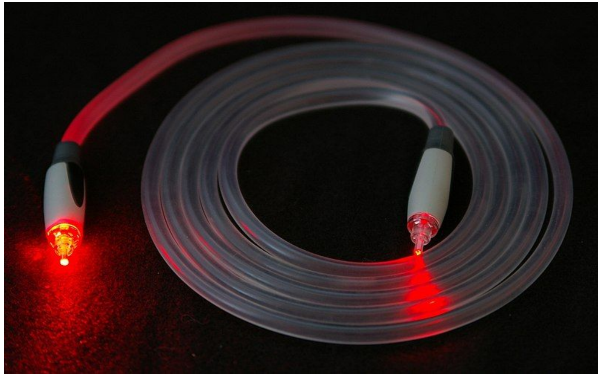
- When $n_1 > n_2$, above the critical angle, there is no solution
- Total internal reflection captures the light in medium with higher refraction index



# Simple optical fibers – total internal reflection

- Total internal reflection captures the light in medium with higher refraction index
- The refraction index of silica glass is around 1.4 – 1.5, of air is 1
- Thin fibers of glass are flexible and can deliver light

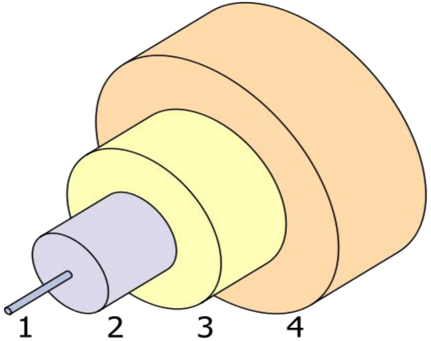



TOSLINK

images from Wikipedia

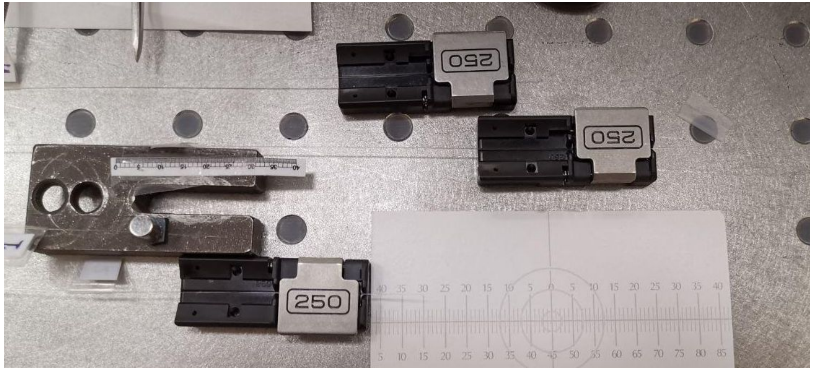
# Optical fibers – structure

- Modern optical fibers do not rely on air, but instead have two or more layers with different refraction index
- The cladding diameter usually ranges between 100 and 500 μm
- Core diameter can be as small as a few wavelengths in singlemode fibers
- Modern fibers are cheap and have extremely low losses (0.2 dB/km)




1. Core: 5–400 μm
2. Cladding: 80–1000 μm
3, 4: protective buffer and jacket

image from Wikipedia




Fibers in the lab

# Optical fibers – types

- Multimode fibers have larger core size, different field patterns (modes) can propagate through the fiber
- In singlemode fibers, the core is thin, fields can only take a specific shape inside the fiber
- Multimode fibers handle much higher power, while singlemode fibers guarantee good beam quality

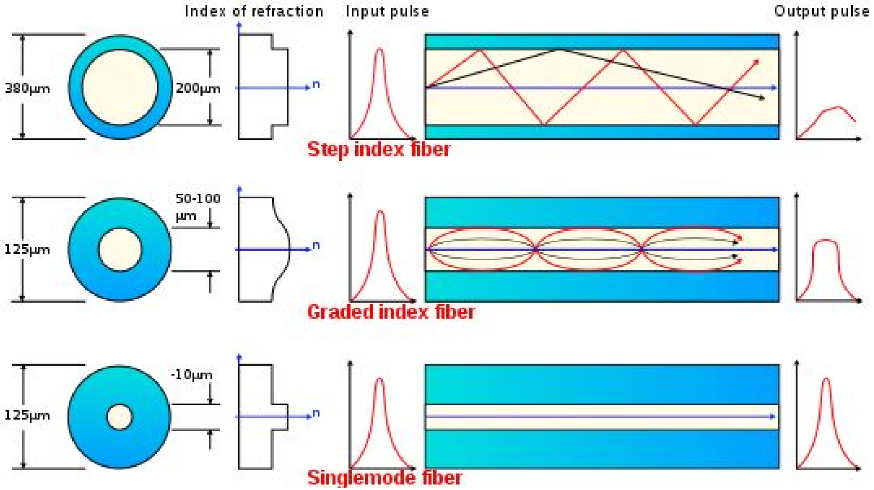



image from Wikipedia

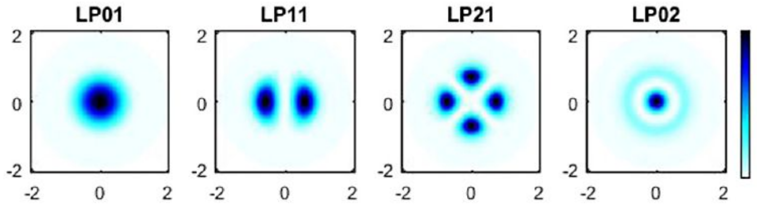
# Fiber modes

- Helmholtz equation governs linear light propagation in a fiber
- Look for z-independent solution for E by separation of the variables
- For the shape *F* we get a boundary value problem, solvable in Bessel functions

$$\nabla^2\tilde{\mathbf{E}} + n^2(\omega)\frac{\omega^2}{c^2}\tilde{\mathbf{E}} = 0$$

$$\tilde{E}_z(r,\omega) = A(\omega)F(\rho)e^{il\phi}e^{i\beta z}$$

$$\frac{d^2F}{d\rho^2} + \frac{1}{\rho}\frac{dF}{d\rho} + \left(n^2k_0^2 - \beta^2 - \frac{l^2}{\rho^2}\right)F = 0$$




Modes for V=5

image from G. P. Agrawal, Nonlinear Fiber Optics

# Fiber modes

- The parameter *V* shows the number of modes

$$V = k_0 a \sqrt{n_1^2 - n_c^2} \qquad k_0 = \frac{2\pi}{\lambda_0}$$

- When *V* is below the critical value, the fiber is singlemode

$$V_c \approx 2.405$$

- For singlemode: $a < \dfrac{2.405\lambda_0}{2\pi\sqrt{n_1^2 - n_c^2}}$
- Example: 1550 nm

$$n_1 - n_c = 0.005$$
$$n_c = 1.5$$

a < ???

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$$n_1 - n_c = 0.005$$

$$n_c = 1.5$$

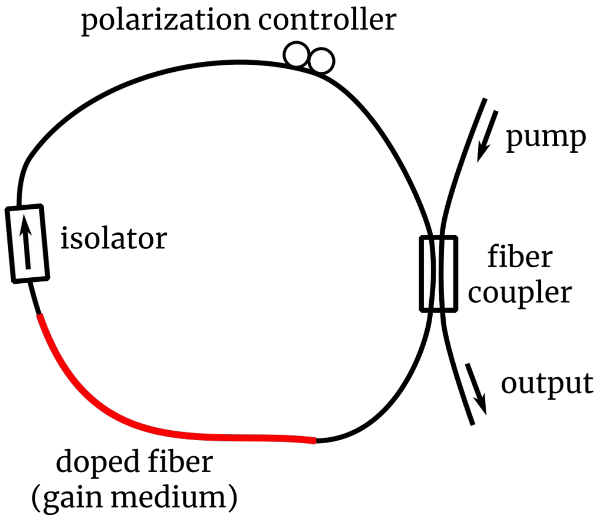
a < 4.8 μm

2009 Nobel Prize for groundbreaking achievements concerning the transmission of light in fibers for optical communication

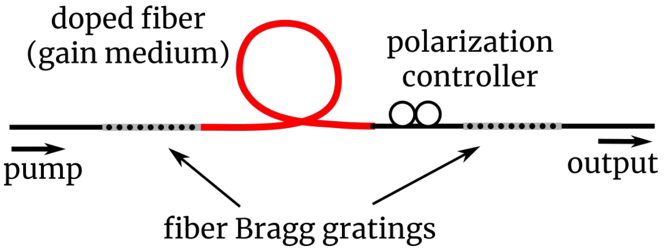
Sir Charles Kao Kuen

# Fiber lasers

- Three main parts of a laser are
  - Gain medium
  - Resonator
  - Pump
- Fibers can be doped to create gain medium
  - Er for 1550 nm
  - Yb for 1030 nm, etc
- Loop the fiber to create feedback
- Pumping can be done with laser diodes




Simplest fiber laser

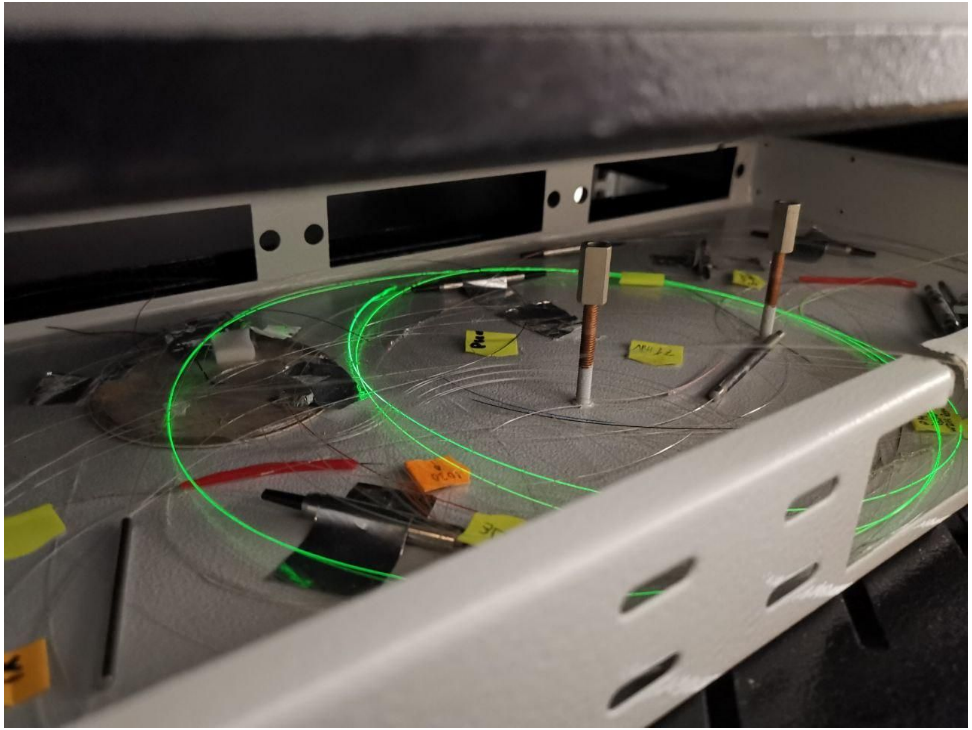



Bragg gratings to create feedback

# Fiber lasers

- Simple, small, and robust
- Provide good beam quality
- High pumping efficiency
- Easy to cool down
- Easy to deliver the beam

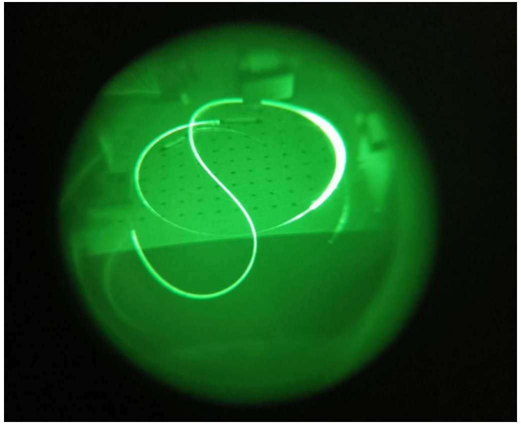
- Typically, low peak power



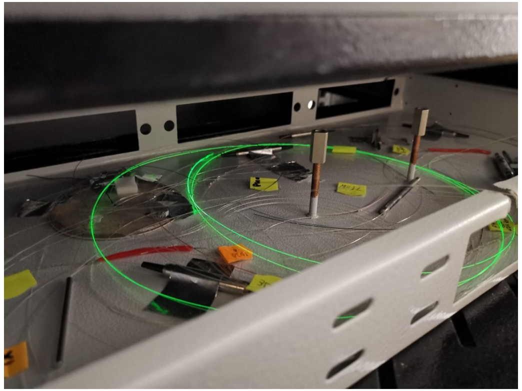
Fluorescence of Er-doped fiber laser

# Fiber lasers


10 kW ytterbium-doped fiber laser system



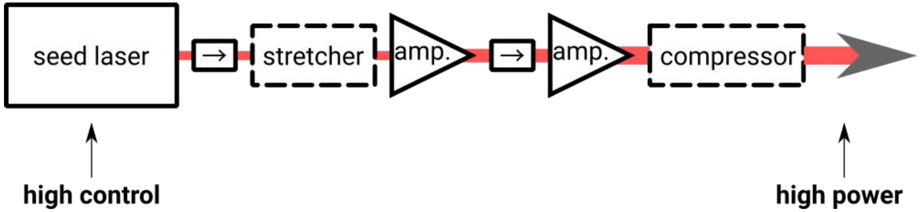
Fluorescence of Yb-doped fiber amplifier through IR viewer



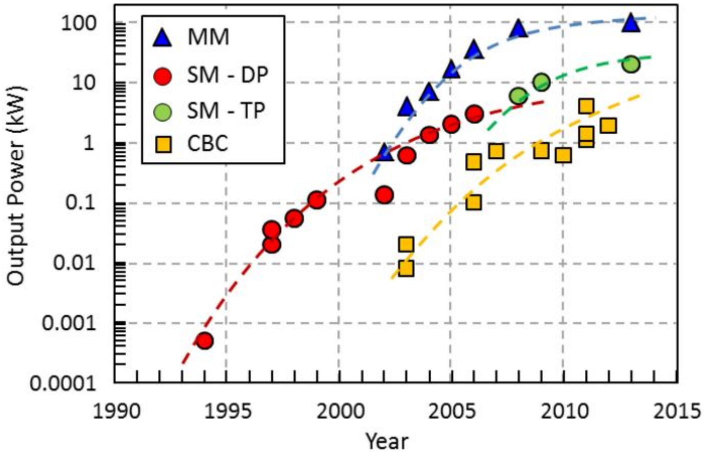
Fluorescence of Er-doped fiber laser

# High-power fiber lasers

- Master oscillator, power amplifier scheme (MOPA)
- CW fiber lasers reach 10-100 kW




- In pulsed regime, peak power is limited by nonlinear effects
- Chirped-pulse amplification (CPA) is useful
  - stretching and amplifying in the fiber
  - compressing in free space




Progress of CW fiber lasers

image from M. N. Zervas, C. A. Codemard, IEEE J. Sel. Top. Quantum Electron., 20(5), 219, 2014

# Kerr effect

- When the electric field is strong enough, the induced polarization in the medium is no longer proportional to the electric field
- In isotropic media such as glasses, the third-order nonlinearity is the lowest
- The change can be induced both by external electric field and by self-action (optical Kerr effect)
- Effectively, the refraction index is changed proportionally to the intensity
- Kerr effect leads to a number of effects in time and space

$$\mathbf{P}(t) = \varepsilon_0 \left( \chi^{(1)} \mathbf{E}(t) + \chi^{(2)} \mathbf{E}^2(t) + \chi^{(3)} \mathbf{E}^3(t) + \ldots \right),$$

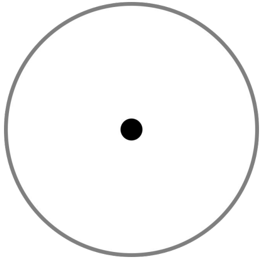
$$\tilde{n} = n + \bar{n}_2 |E|^2$$

# Self-focusing

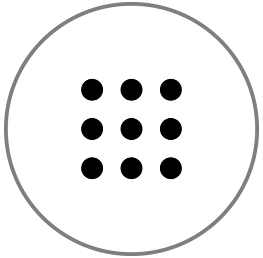
- Kerr effect leads to self-focusing in fibers
  - Refraction index in the center is increased due to the Kerr effect
  - Light is more tightly focused due to the changes in refraction index
  - Positive feedback is created
- At low power, diffraction is stronger
- Above critical power, the beam collapses
- Critical power is at the order of MW for silica fibers
- Example:
  - 400 fs sech-shaped pulses
  - Average power 400 mW
  - Repetition rate 0.5 MHz
  - Peak power 1.7 MW
- Possible solutions:
  - coherent combining
  - special fibers

# Multicore fibers

- It is possible to create fibers with more than one core
- If the cores are far apart, light propagates in each core independently
  - Effectively, N individual fibers in a single bundle
  - Allows for power scaling, but phase stabilization is required
- If the cores are close to each other, light propagates coherently in all cores
  - Phase is stable
  - Nonlinear effects on a larger scale



Single-core fiber



Multicore fiber

# Supermodes in coupled-core MCFs

- In weakly coupled MCFs, fields can be approximated by the sum of fields of modes in each core, with some coefficients

- Due to overlap, the equations for the envelope in each mode are coupled

$$\frac{dA_i(z)}{dz} = i\Delta\beta_i A_i(z) + \sum_{j\neq i} i c_{ij} A_j$$

- In matrix form,

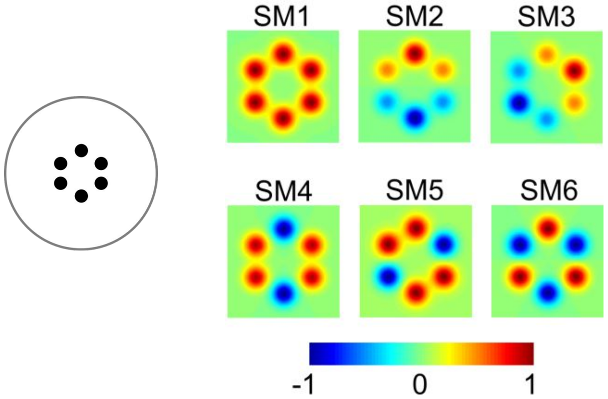
$$\frac{dA}{dz} = iCA, \quad C = \begin{pmatrix} \Delta\beta_1 & c_{12} & \cdots & c_{1N} \\ c_{21} & \Delta\beta_2 & \cdots & c_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ c_{N1} & c_{N2} & \cdots & \Delta\beta_N \end{pmatrix}$$

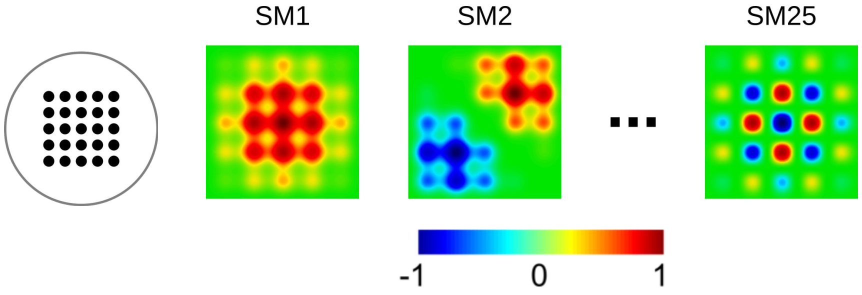
# Supermodes in coupled-core MCFs

- The eigenvalues of $A$ are called supermodes

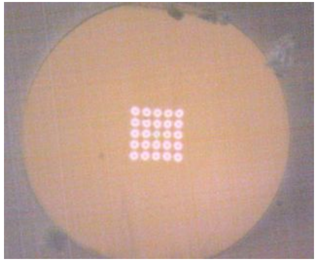
$$\frac{dA}{dz} = iCA$$

- In MCF with N single-mode cores there are N supermodes

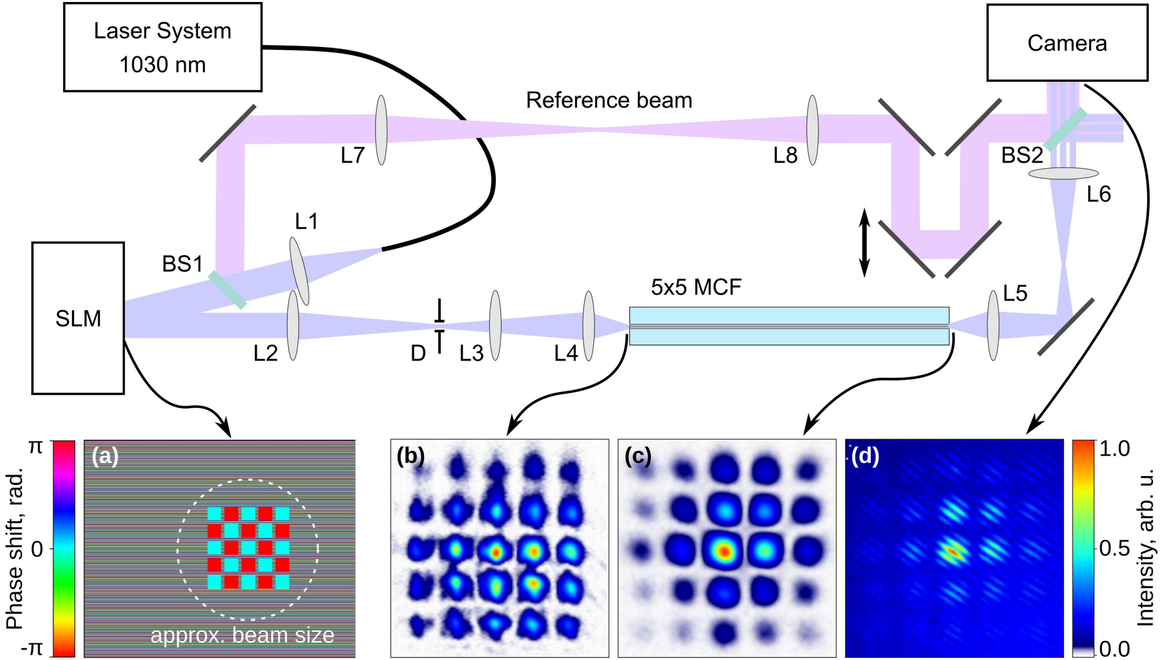


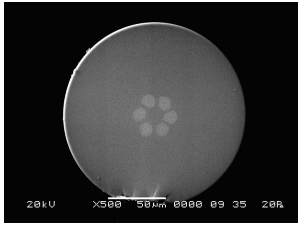
# Excitation and analysis of supermodes in an MCF



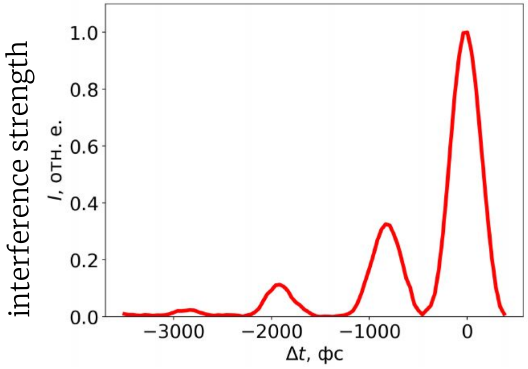
25-core MCF

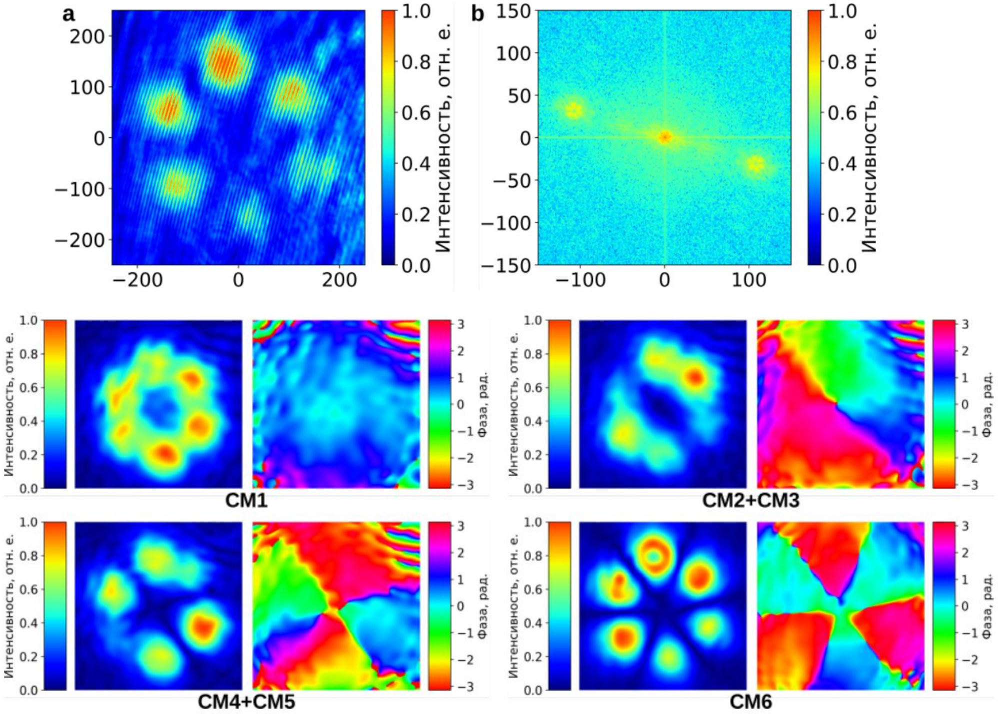


# Excitation and analysis of supermodes in an MCF



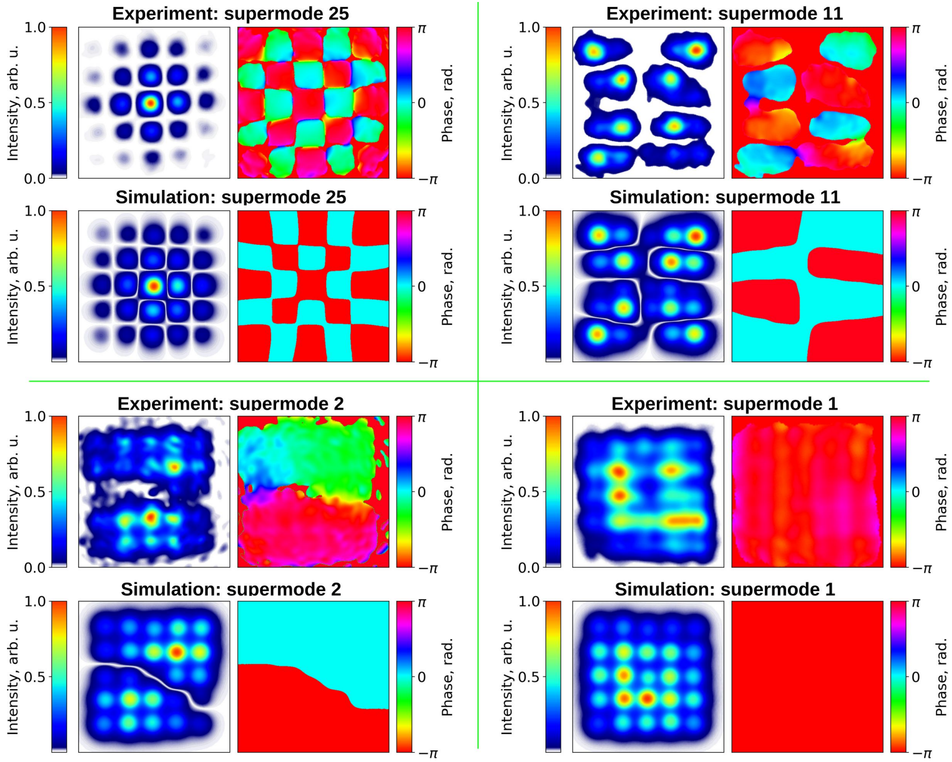

6-core MCF



# Excitation and analysis of supermodes in an MCF

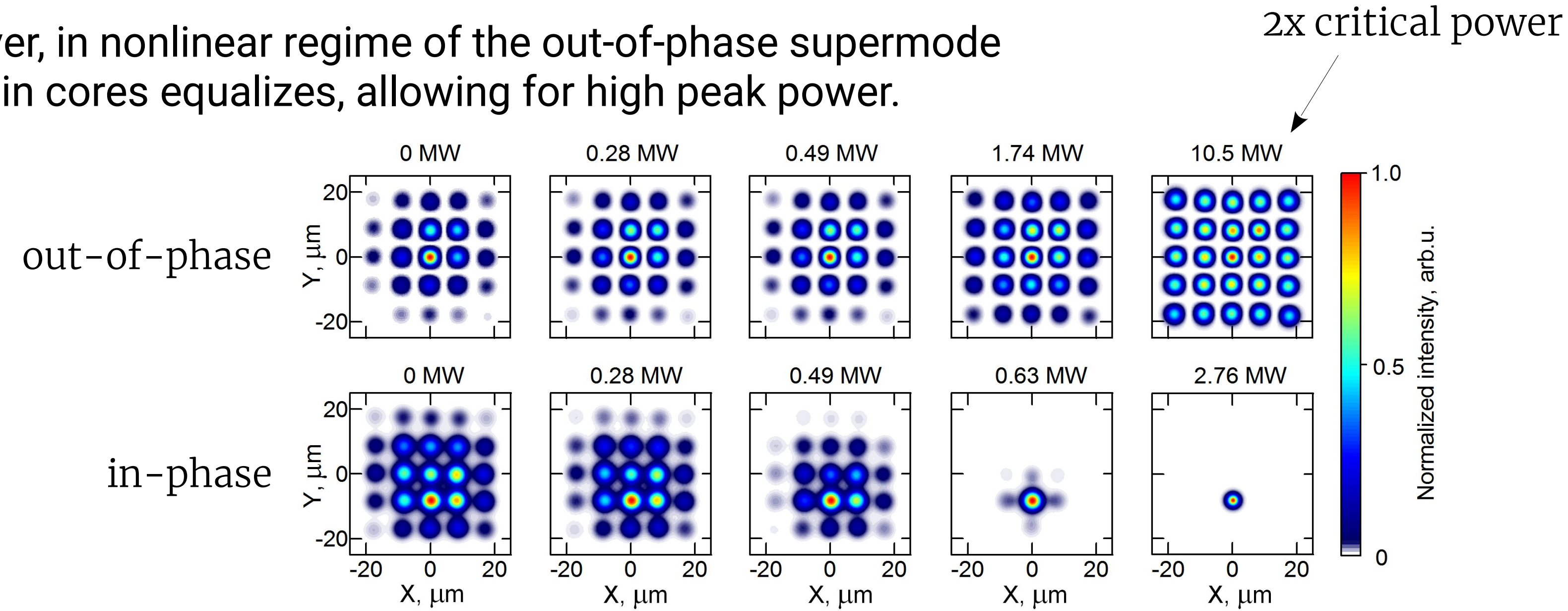
- We used stochastic gradient descent to find an SLM phase mask to maximize selectivity of out-of-phase and in-phase supermodes excitation
- 90% of pulse energy in the out-of-phase supermode achieved




N. A. Kalinin, et al.
Photonics, 8, 314, 2021

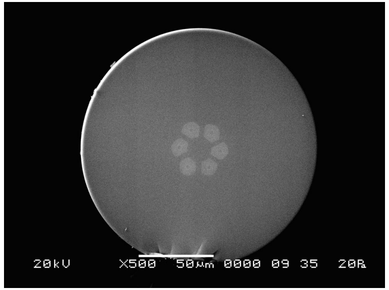
# High-power stability

- Discrete self-focusing effect can limit total power in MCF, as in the in-phase supermode regime.
- However, in nonlinear regime of the out-of-phase supermode power in cores equalizes, allowing for high peak power.



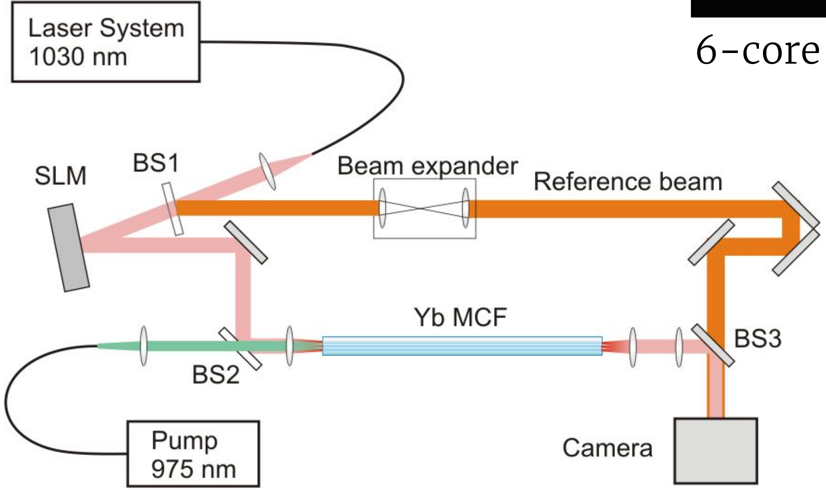
# Out-of-phase supermode amplification, 6-core MCF

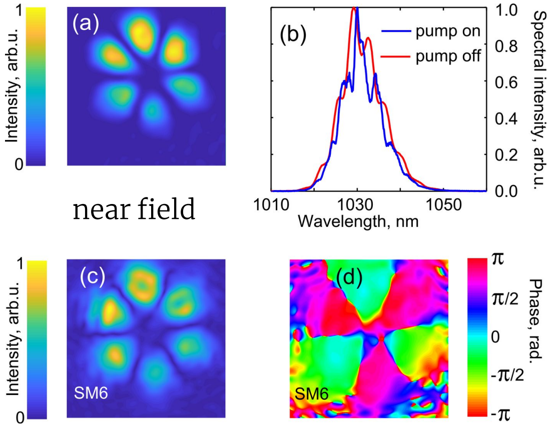
- Pulse energy up to ~0.9 μJ
- Pulse duration ~50 ps
- Estimated peak power ~18 kW




6-core Yb-doped MCF

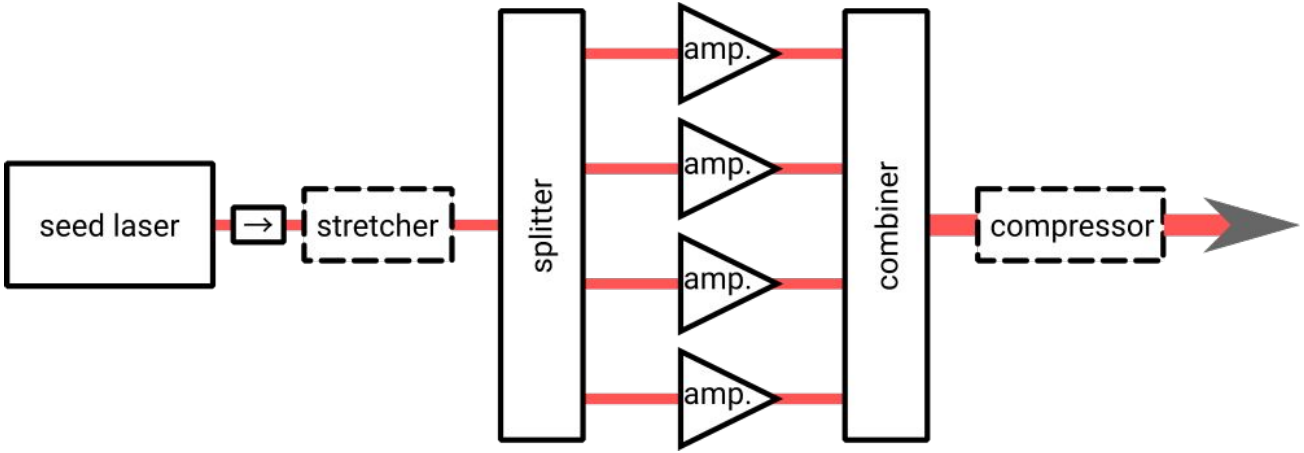
A. V. Andrianov, et al.
J. Light. Technol., 38(8), 2464, 2020



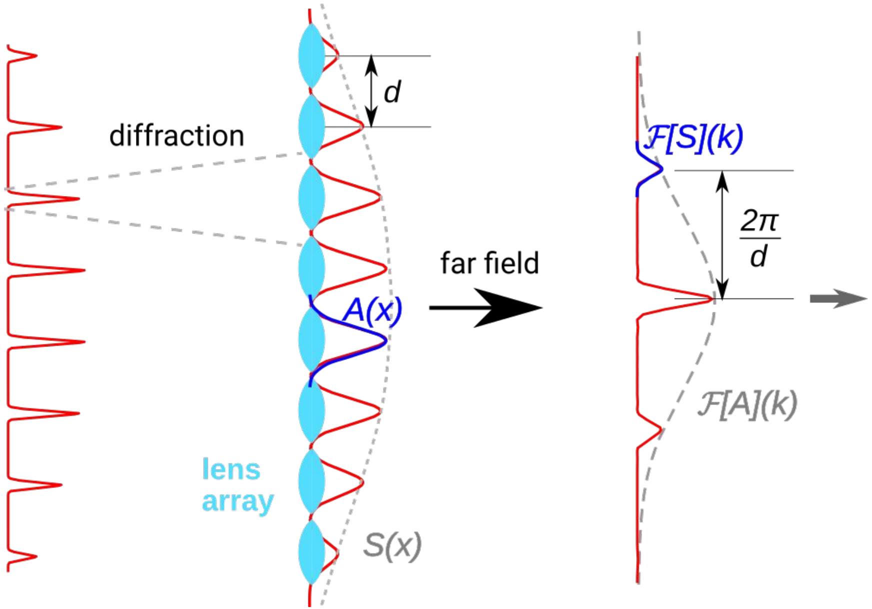
# Coherent beam combining (CBC)

- Another approach for high power lasers is to combine many beams into a single one



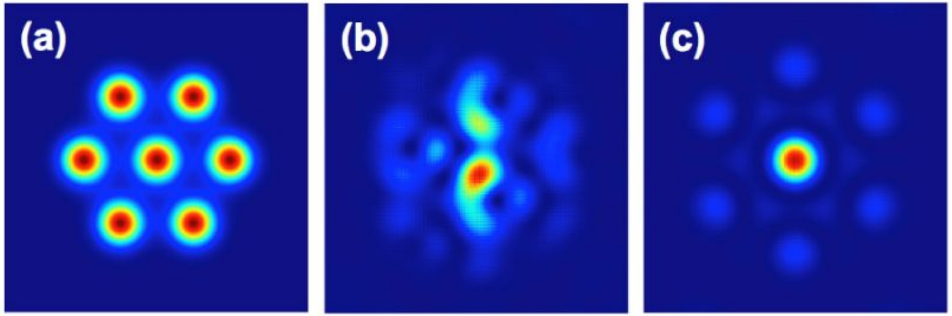
# Coherent beam combining (CBC)

- Most versatile approach is tiled aperture



# Coherent beam combining (CBC)

- The channels need to be in phase
- Phase stabilization system up to 10 kHz bandwidth is needed

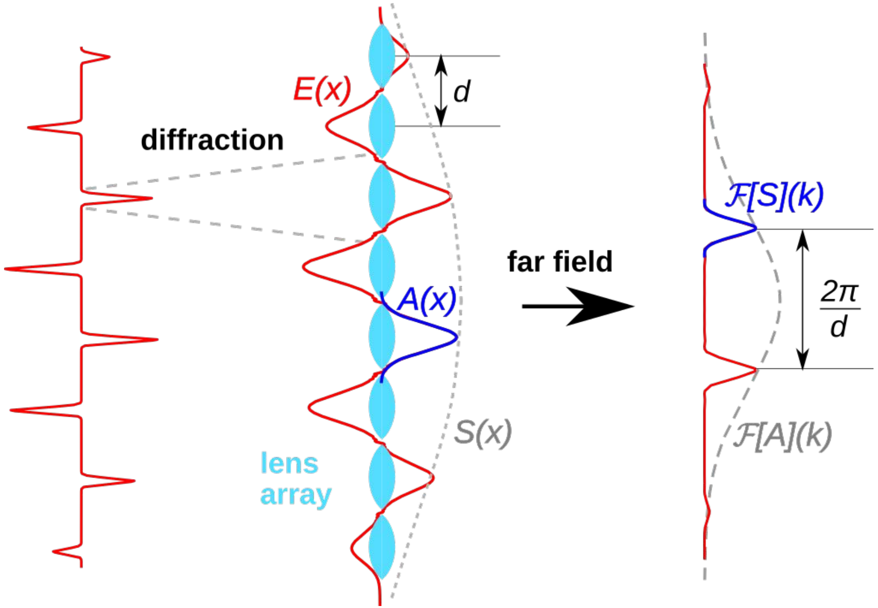


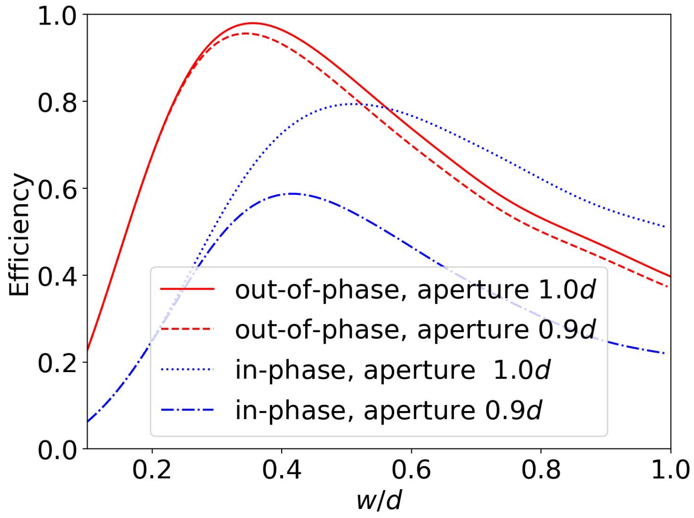

7-core Yb-doped independent-core MCF: near field, far field no phase control, in-phase far field

image from Ramirez L P et al 2015, Opt. Exp. 23 5406–16

# Out-of-phase tiled aperture CBC

- Flipping the phase of every second beam is more efficient



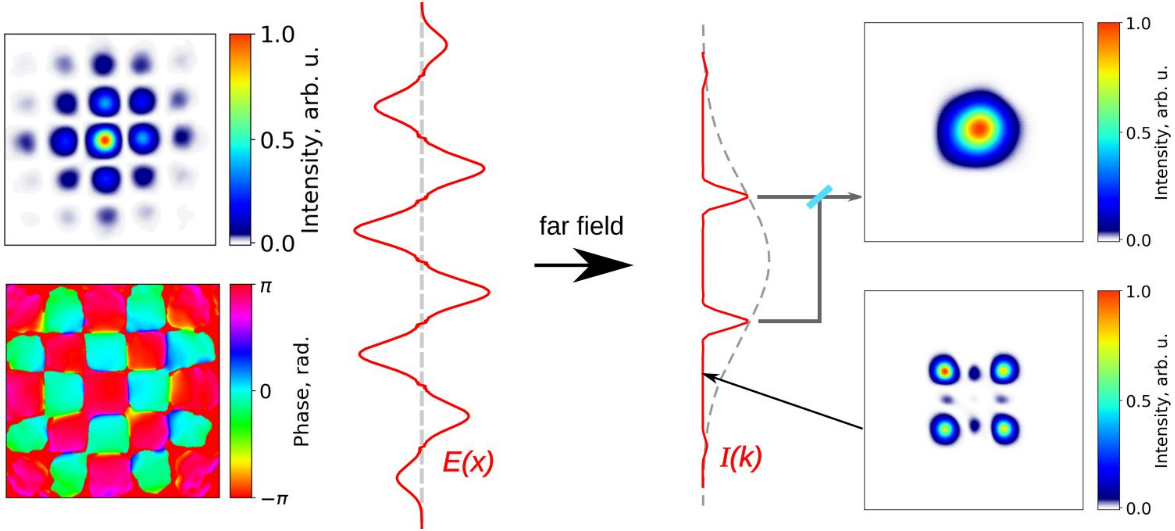




A. V. Andrianov, et al.
Opt. Lett., 45(17), 4774, 2020

# Coherent combining of the out-of-phase supermode

- Use the out-of-phase regime of tiled aperture scheme
- No lens array is needed because of high fill factor
- Combining efficiency 93%, $M^2$=1.09 (simulation)

out-of-phase supermode (experiment)

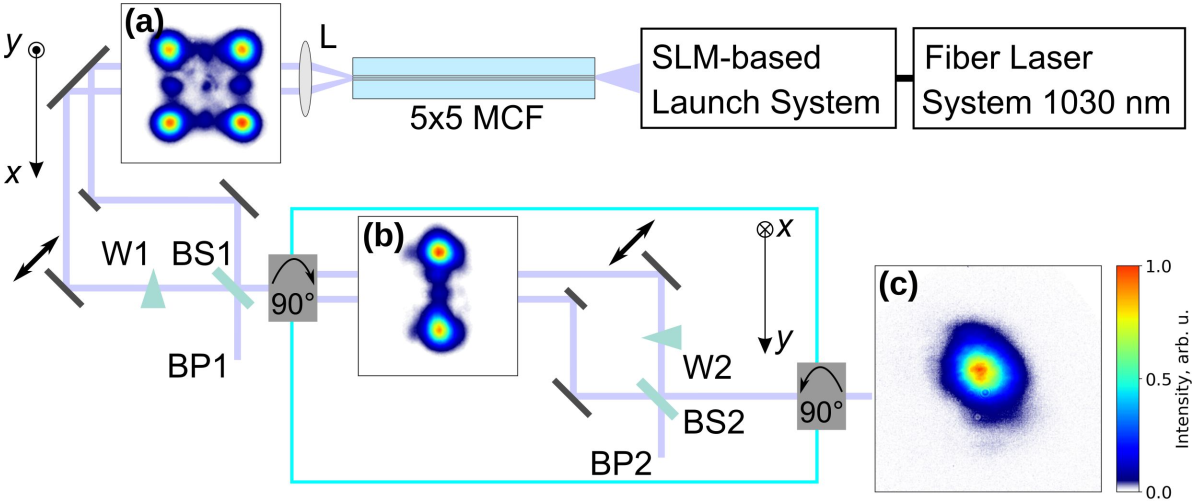



combined beam (simulation)

far field intensity (simulation)

# Coherent combining of the out-of-phase supermode

- Two steps of combining, a delay line to match group delay, and a wedge to match phase in each step
- Combining efficiency 73%, $M^2$ = 1.3 (experiment)




N. A. Kalinin, et al.
Opt. Express, 30, 1013, 2022

# Thank you!

# Questions? ⟶ nikolay.kalinin@mpl.mpg.de