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Investigation of Mode Coupling Introduced by Forward Rayleigh Scattering

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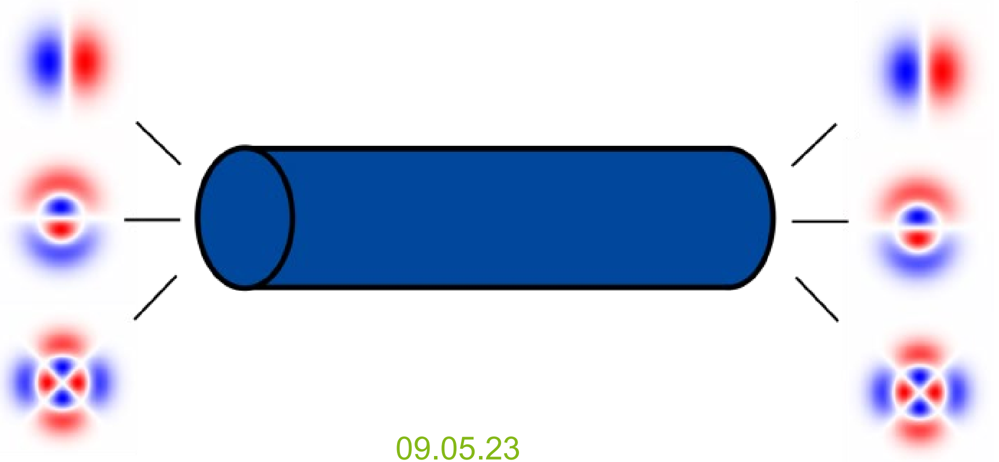
Inhalt

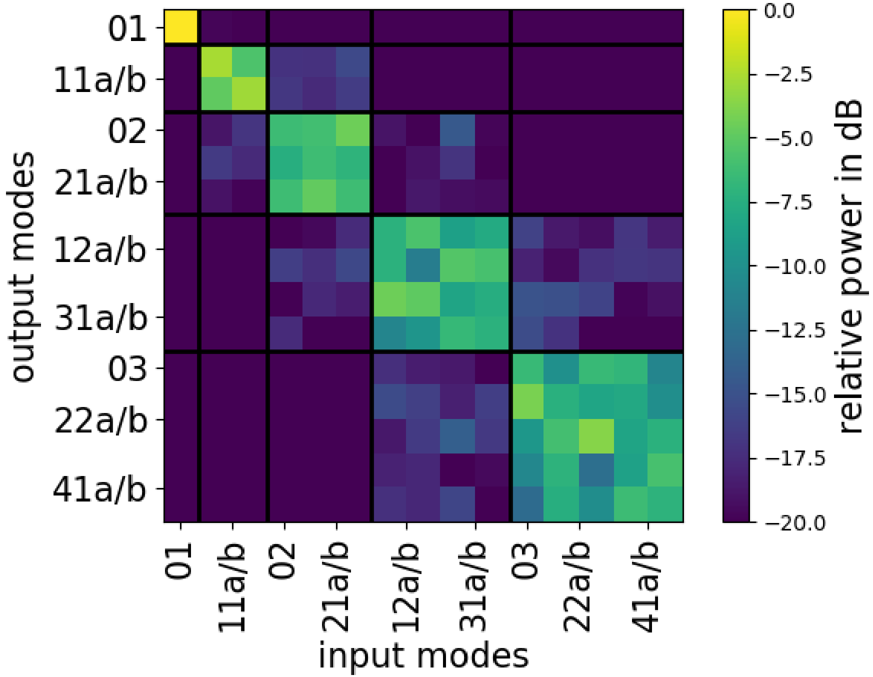
- Motivation
- Mode coupling and MIMO in MMFs
- Investigation of forward Rayleigh scattering
  - Recapture factor
  - Cross Talk
  - Power Transfer Matrix
- Comparison with measurements
- Conclusions

Motivation

- Mode-division multiplexing (MDM) is a promising solution for increasing the fiber capacity.
- Fiber modes are used as propagation channels



Measured Power Transfer Matrix (Graded-Index Fiber)

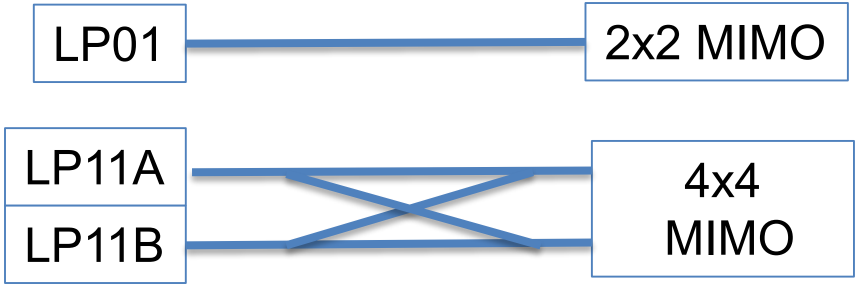


- Strong coupling between modes inside a mode group
- Weaker coupling between mode groups

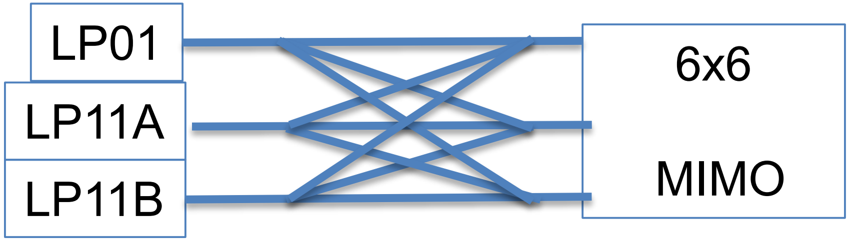
Mode Coupling and MIMO

- Inter group coupling <~-17 dB:
  - Reduced MIMO approach
- Inter group coupling >~-17 dB:
  - MIMO across all modes
  - Strong coupling reduces DMGDs

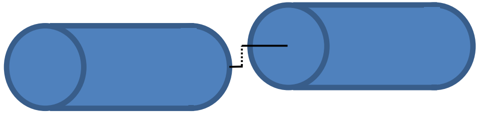
reduced MIMO approach



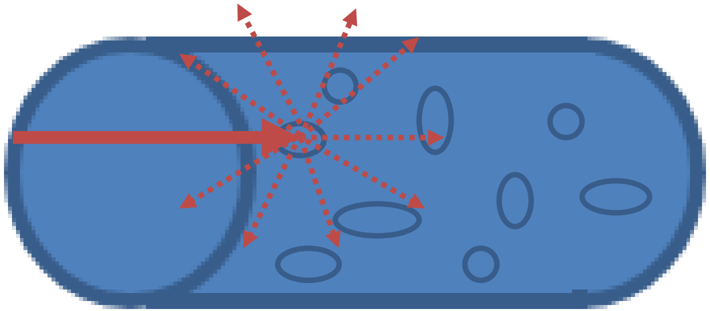
MIMO across all transmitted modes



Mode coupling mechanisms



- Macroscopic perturbation effects
  - Core ellipticity, offset, bending…
- Microscopic perturbation effects
  - Micro bending
  - Rayleigh scattering
    - Scattering outside fiber -> loss
    - Scattering in backward direction -> RBS
    - Forward scattering into different modes –> Mode coupling



- Is the reduced MIMO approach limited by mode coupling introduced by forward Rayleigh scattering ?

Recapture-Factor S

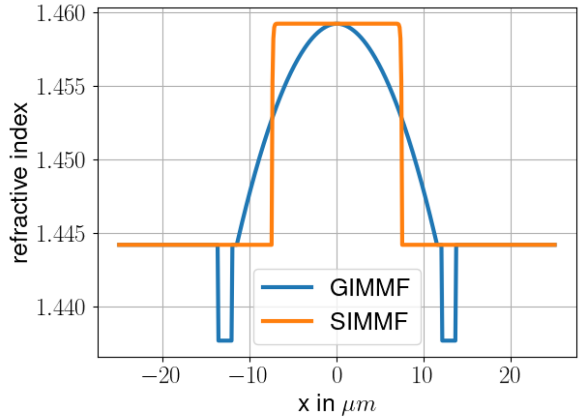
- Proportion of power scattered from mode m into mode n

- Major dependence: overlap integral of power densities

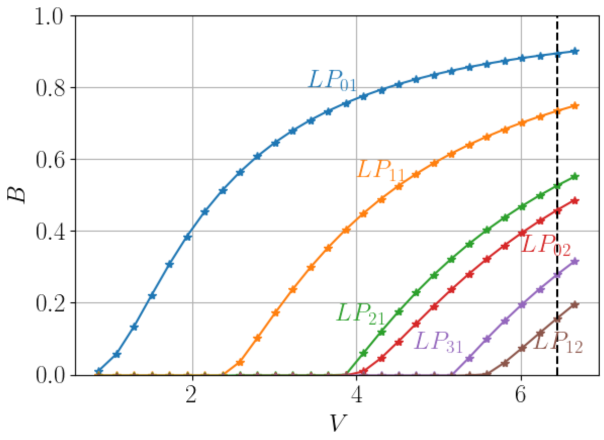
- $S_{m,n} = \frac{3\pi c^2}{2 < n >^2 \omega^2} \int\int \left(E'_{x,n}\right)^2 \left(E'_{x,m}\right)^2 dxdy$

- For high recapture factor:
  - Small mode field diameter
  - Large overlap between mode fields m and n

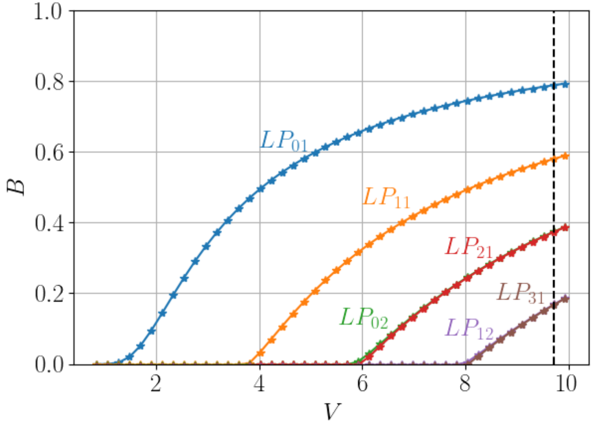
Investigated 10-mode fibers with NA=0.2



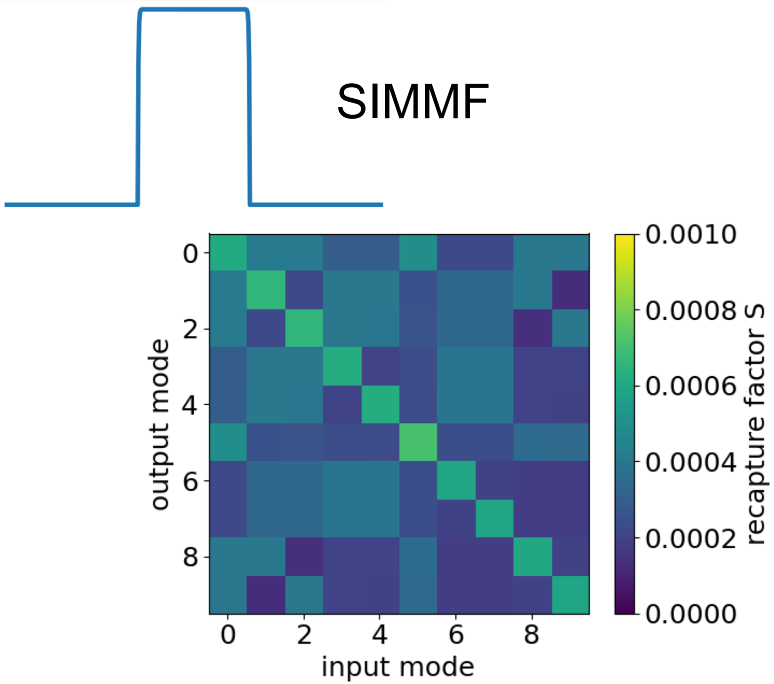
SIMMF

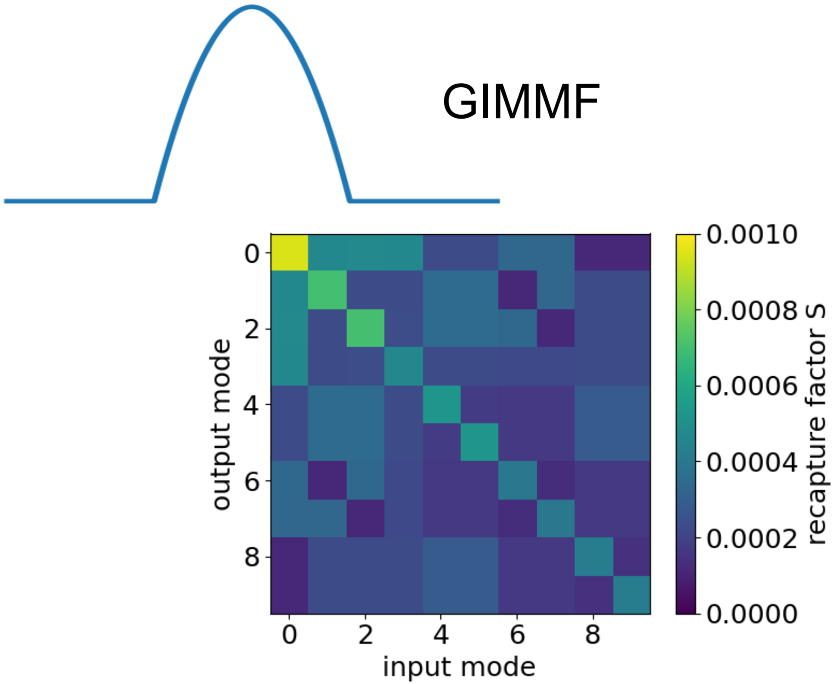


GIMMF



Recapture factor matrix





Mode Dependent XT-Powers

- All 10 modes are excited with the same power
- All 10 modes have the same overall attenuation

$$\alpha = 0.2 \frac{dB}{km} \qquad \alpha_S = 0.16 \frac{dB}{km}$$

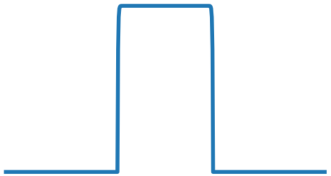
Incoherent scattering process:

- $\mathrm{XT_m} = \frac{power\ scattered\ into\ mode\ m}{power\ propagating\ in\ mode\ m}$

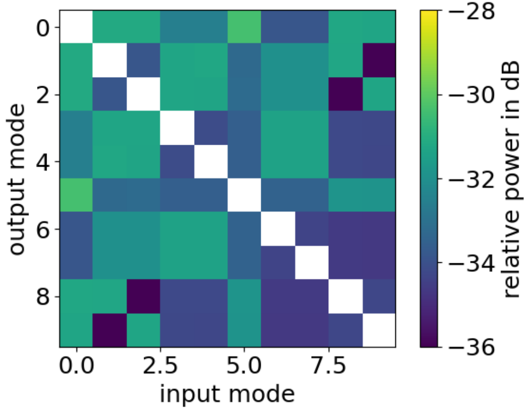
->XT_m increasing linearly with fiberlength

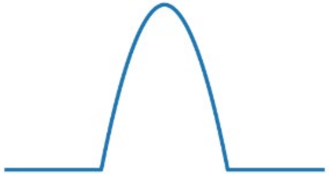
48 km: SIMMF: max XT: -22.3 dB GIMMF: max XT: -22.8 dB

Simulated power transfer matrix after 48 km

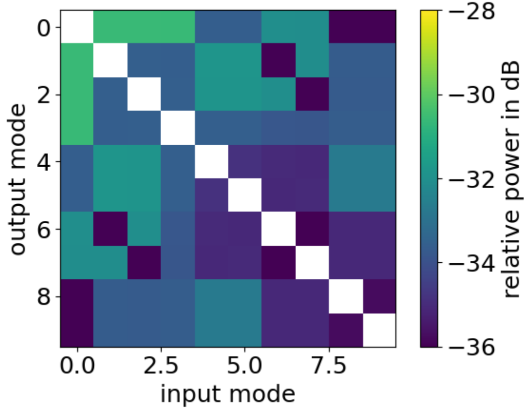


SIMMF





GIMMF



Avg. off main diagonal: -32.61 dB

Avg. off main diagonal: -33.41 dB

Measured power transfer matrix of 48 km of 10-mode SIMMF

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257-Tbit/s Weakly Coupled 10-Mode C + L-Band WDM Transmission

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TABLE I
MEASURED MODAL XT IN A 10-MODE MULTIPLEXER/DE-MULTIPLEXER AT 1550 NM

Unit: dB	LP01 out	LP11a out	LP11b out	LP21a out	LP21b out	LP02 out	LP31a out	LP31b out	LP12a out	LP12b out
LP01 in	—	-21.2	-21.2	-25.4	-25.4	-20.5	-29.3	-29.3	-24.4	-24.4
LP11a in	-22.1	—	—	-21.9	-21.9	-23.4	-27.5	-27.5	-28.5	-28.5
LP11b in	-19.5	—	—	-20.8	-20.8	-20.7	-25.4	-25.4	-23.2	-23.2
LP21a in	-28.7	-20.7	-20.7	—	—	-23.8	-22.0	-22.0	-23.7	-23.7
LP21b in	-25.6	-22.1	-22.1	—	—	-25.8	-23.4	-23.4	-22.3	-22.4
LP02 in	-20.3	-20.8	-20.8	-22.7	-22.7	—	-23.8	-23.8	-24.0	-24.0
LP31a in	-25.6	-22.9	-22.9	-21.8	-21.8	-26.2	—	—	-24.7	-24.7
LP31b in	-26.1	-23.1	-23.1	-22.5	-22.5	-21.1	—	—	-24.5	-24.5
LP12a in	-27.9	-25.6	-25.6	-22.4	-22.4	-20.0	-23.2	-23.2	—	—
LP12b in	-21.7	-22.4	-22.4	-21.0	-21.0	-20.9	-22.9	-22.9	—	—

B2B: -23 dB avg. off main diagonal

$$M_{B2B} = M_{mux} * M_{demux}$$

$$M_{48km} = M_{mux} * M_{fiber} * M_{demux}$$

TABLE III
MEASURED MODAL XT IN A 48-KM 10-MODE FIBER WITH A 10-MODE MULTIPLEXER/DE-MULTIPLEXER PAIR AT 1550 NM

Unit: dB	LP01 out	LP11a out	LP11b out	LP21a out	LP21b out	LP02 out	LP31a out	LP31b out	LP12a out	LP12b out
LP01 in	—	-16.9	-18.6	-24.6	-24.1	-16.6	-22.8	-24.7	-22.6	-22.2
LP11a in	-17.5	—	—	-17.0	-16.0	-14.6	-20.4	-23.7	-19.8	-20.2
LP11b in	-14.8	—	—	-17.2	-16.1	-13.6	-18.7	-21.4	-19.0	-19.1
LP21a in	-22.1	-14.3	-15.3	—	—	-14.7	-12.5	-14.5	-18.9	-16.3
LP21b in	-22.8	-16.3	-17.7	—	—	-16.5	-13.5	-15.3	-19.9	-17.2
LP02 in	-16.9	-14.6	-17.9	-17.2	-17.2	—	-19.1	-20.8	-15.8	-15.9
LP31a in	-23.0	-21.4	-21.2	-14.8	-15.7	-20.6	—	—	-17.6	-18.2
LP31b in	-24.9	-23.0	-22.7	-16.6	-18.1	-20.2	—	—	-19.7	-20.1
LP12a in	-23.3	-22.6	-24.1	-17.8	-18.1	-14.5	-15.5	-18.8	—	—
LP12b in	-20.8	-21.5	-22.3	-19.3	-19.6	-15.2	-16.4	-19.5	—	—

48 km: -17 dB avg. off main diagonal

-> Transmission matrix: ~ -25 dB off main diagonal (all linear mode copuling effects)

Mode coupling by Rayleigh scattering is ~ 8 dB lower

Conclusions

- Mode coupling by Rayleigh scattering is not likely to be further reduced in the future
- Lower bound for linear mode coupling
- Step-index fibers more affected than graded-index fibers
- XT increases linearly with fiber length due to incoherent process
- Reduced MIMO approach limited to fiber length < ~500 km (10 modes)

Thank you for your attention!