TRANSMISSION IN SPACE-DIVISION MULTIPLEXED SYSTEMS

Roland Ryf, Haoshuo Chen, and Nick Fontaine

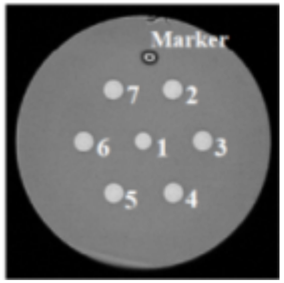
Bell Laboratories, Alcatel-Lucent, Holmdel (NJ), USA

Alcatel·Lucent

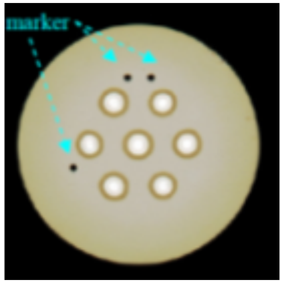
OVERVIEW OF SDM FIBERS

“Uncoupled” multi-core fibers

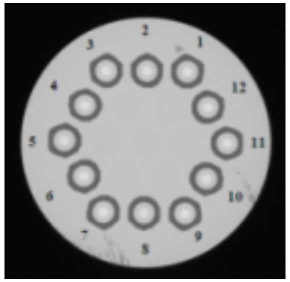
B.Zhu et al., ECOC 2011



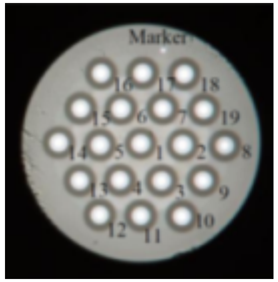
T. Hayashi et.al., ECOC 2011



K.Imamura et al., ECOC 2011



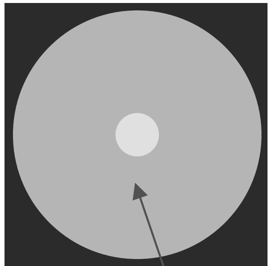
H. Takara et al., ECOC 2012



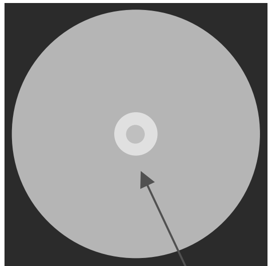
Sakaguchi et al., OFC 2012

Coupled multi-core and few-mode fibers

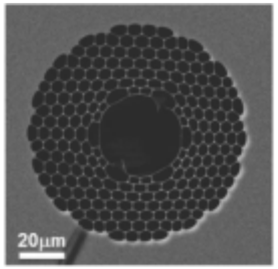
R. Ryf et al., OFC 2012



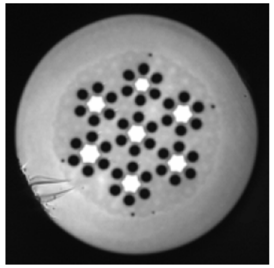
R. Ryf et al., OFC 2013



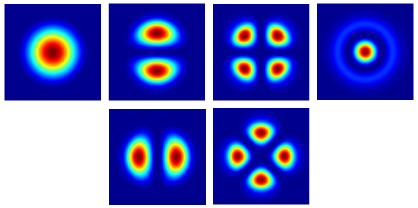
N.K. Fontaine et.al., Sum.Top. 2013

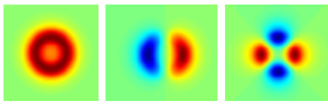


M. N. Petrovich et.al., ECOC 2012

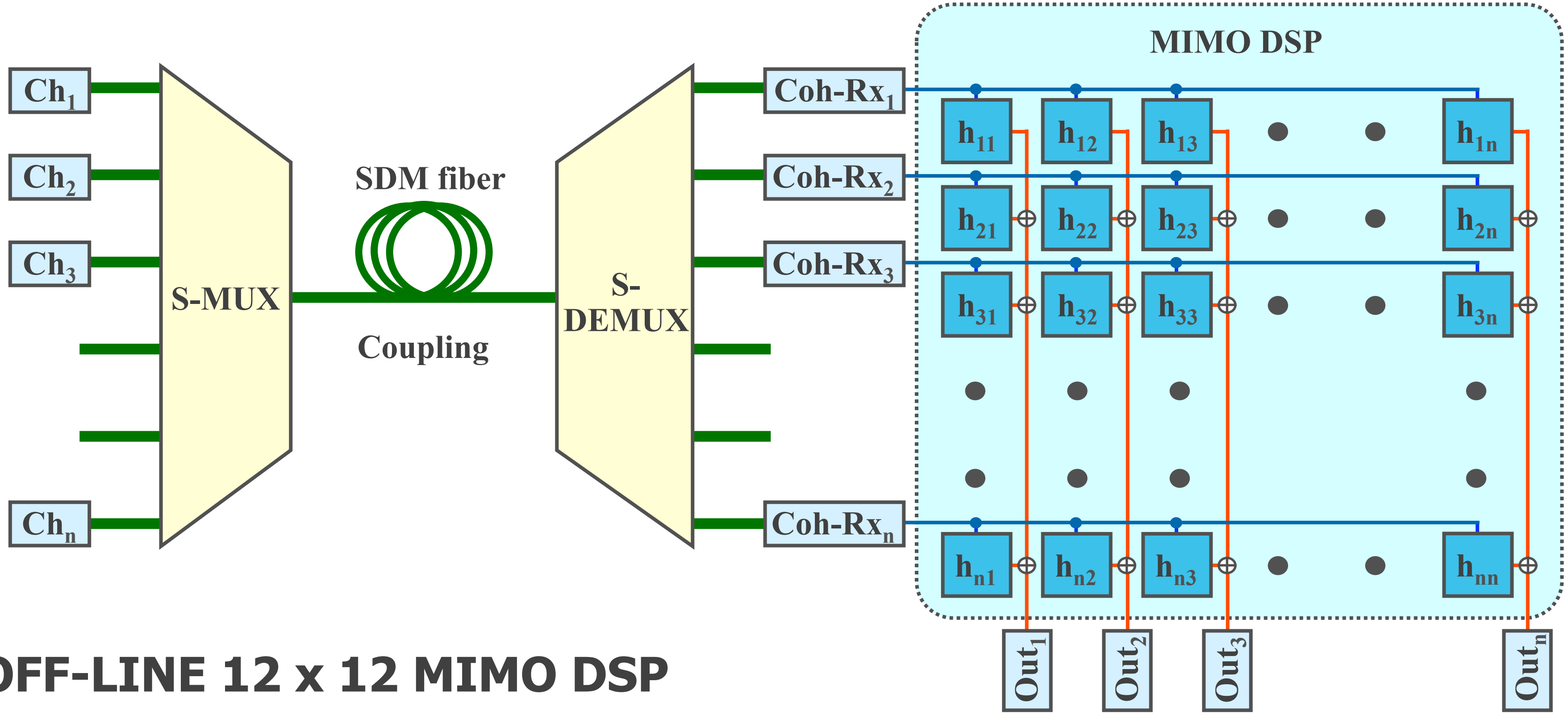


C. Cia et al., Sum. Top. 2012





COHERENT MIMO BASED SDM TRANSMISSION



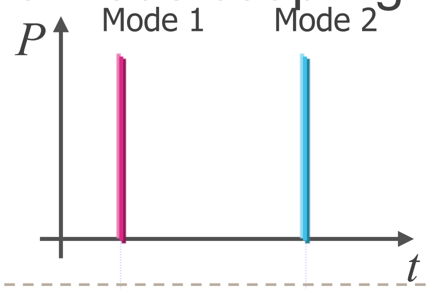
OFF-LINE 12 x 12 MIMO DSP

- Adaptive T/2-spaced frequency-domain 6x6 MIMO equalizer (1000 taps)
- Data-aided coefficient acquisition using least-mean-square algorithm (LMS)
- Coefficient tracking using constant-modulus algorithm (CMA)

S. Randel et al, ECOC 2013

IMPACT OF MODECOUPLING ON IMPULSE RESPONSE

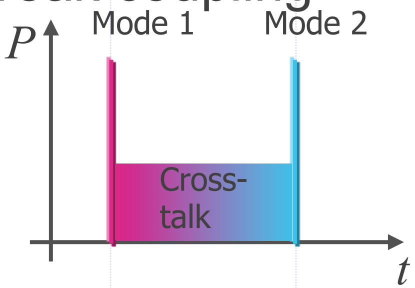
- No mode coupling



-Modes are completely separated, light stays in the mode it was launched to

M. Salsi et.al., OFC 2012, OTu2C.5

- Weak coupling



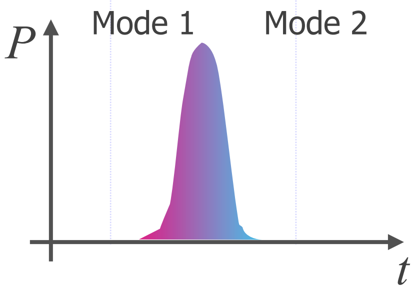
-Some of the light couples from one mode to another

-The impulse response is bound by the maximum DGD of the modes

-Crosstalk appears like random noise

-Time axis correspond to a location in propagation direction were the crosstalk occurs

- Strong Coupling



-Full extend of DGD is never realized, as the light continuously couples between modes

-Impulse response width is less than nominal DGD of the fiber.

-Impulse width will grow with square root of fiber length

Keang-Po Ho, and Joseph M. Kahn, JLT 29(21),2011

L

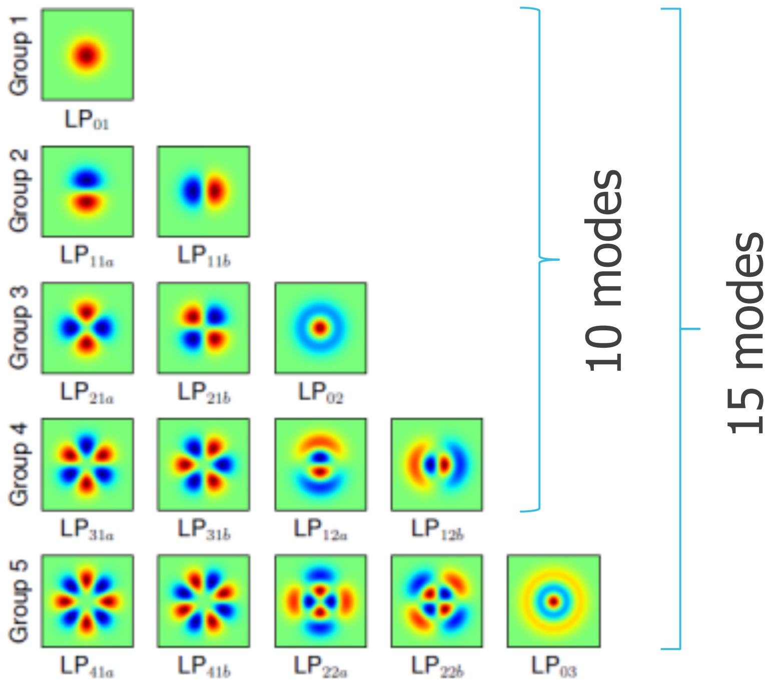
Alcatel·Lucent

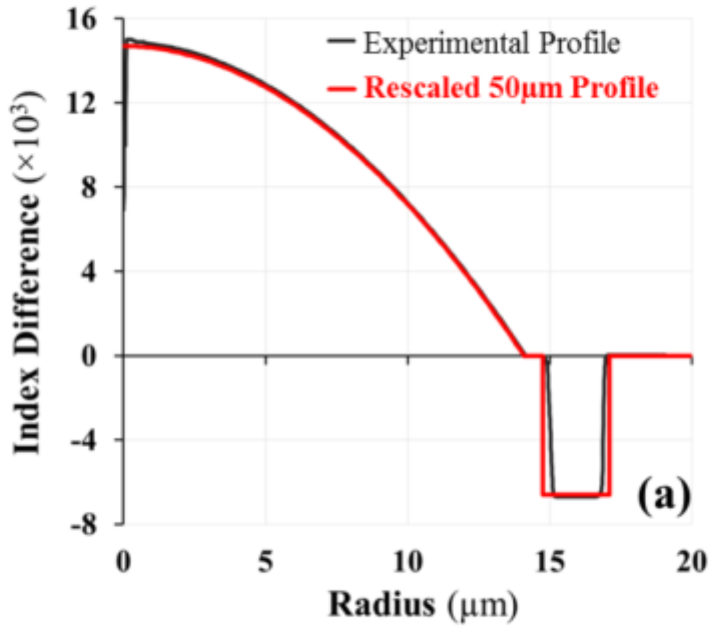
FEW-MODE FIBERS FOR SDM
ADVANTAGES

- Scalable up to >50 modes (15 modes demonstrated)
- Can be spliced with conventional splicer
- Mostly work with regular connectors
- Offers largest number of modes per fiber cross-section
- Standard 125 µm cladding diameter
- **Strong modal overlap allows for cost effective pumping for optical amplification**
- Most free-space components for single-mode fiber can easily be adapted to few mode fibers

  Examples: WSS, AO switch, Splitters, Isolators…

LOW DGD GRADED-INDEX FIBERS



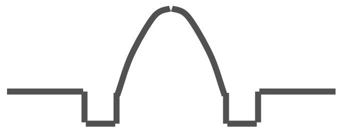


P. Sillard, et.al. OFC201 5, M2C.2

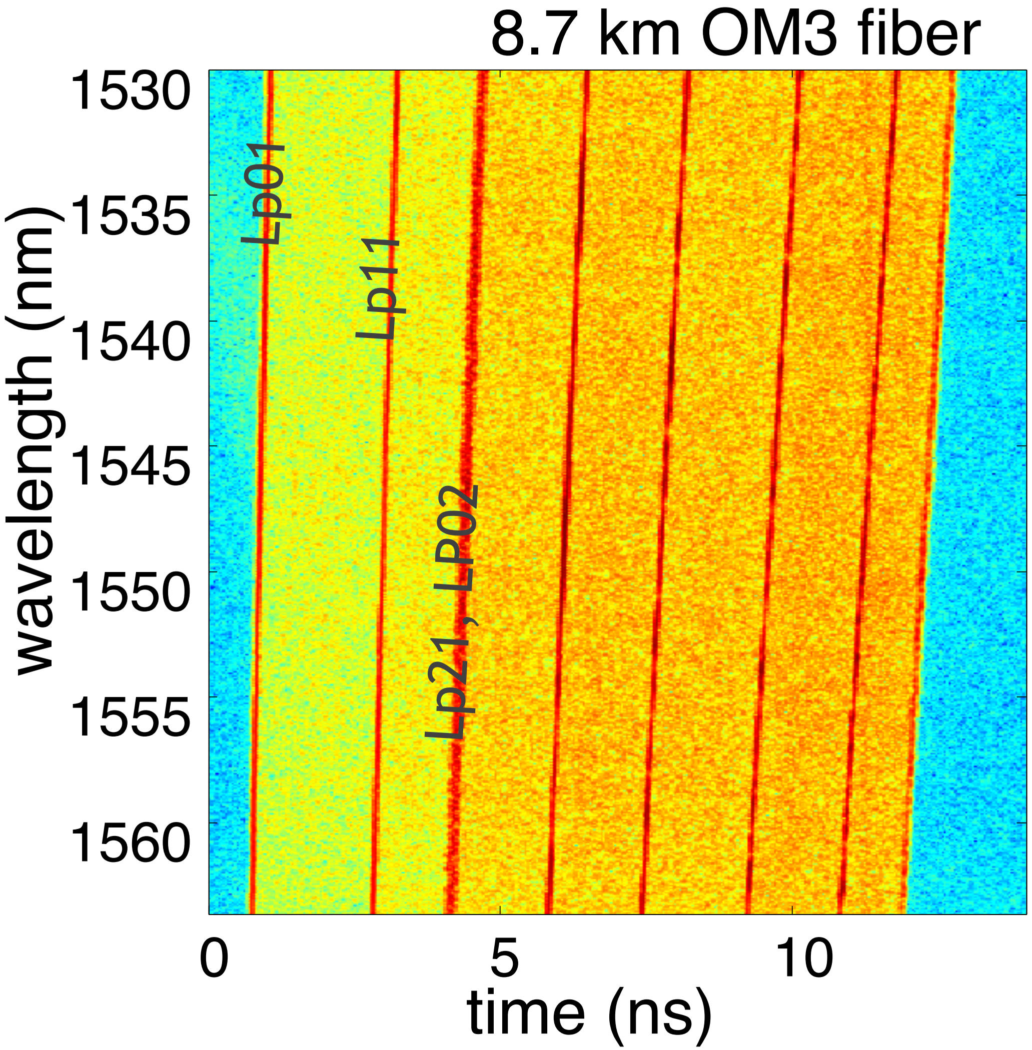
10 modes (6-LP modes): DGD <120 ps/km, Loss 0.22 dB/km, MDL < 0.02 dB/km, CD 19 and 21 ps/nm/km, Aeff 117 to 270 µm^2

15 modes (9-LP modes): DGD <220 ps/km, Loss 0.22 dB/km, MDL < 0.02 dB/km, CD 19 and 21 ps/nm/km, Aeff 95 to 215 µm^2

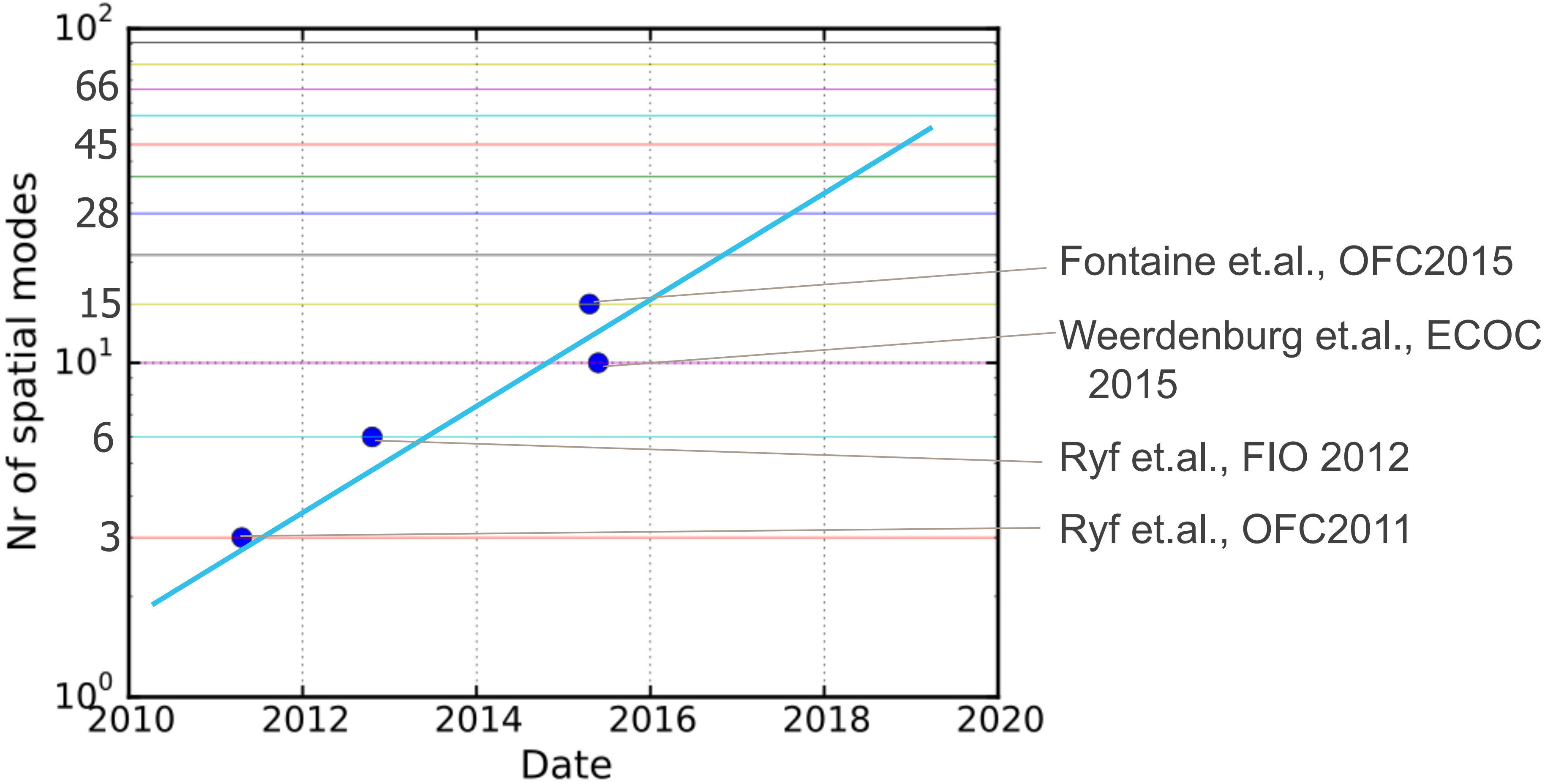
IMPULSE RESONSE SPECTROGRAM



- Graded index profile, 50 μm core diameter, NA = 0.2
- Spectrogram was obtained using swept-wavelength interferometry for an off-axis launch and detection
- Modes are clearly separated and appear as red lines
- LP01 mode is fastest mode
- Modal delays increase with group number
- Clear cut-off after the 8 mode groups => **36 spatial modes**

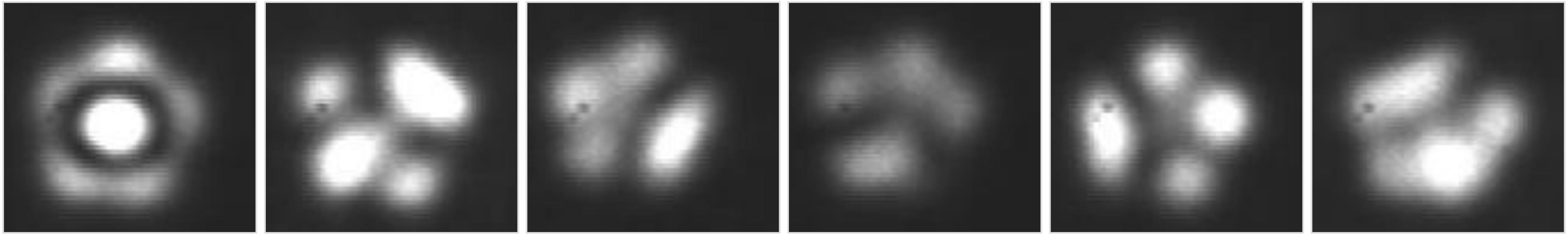


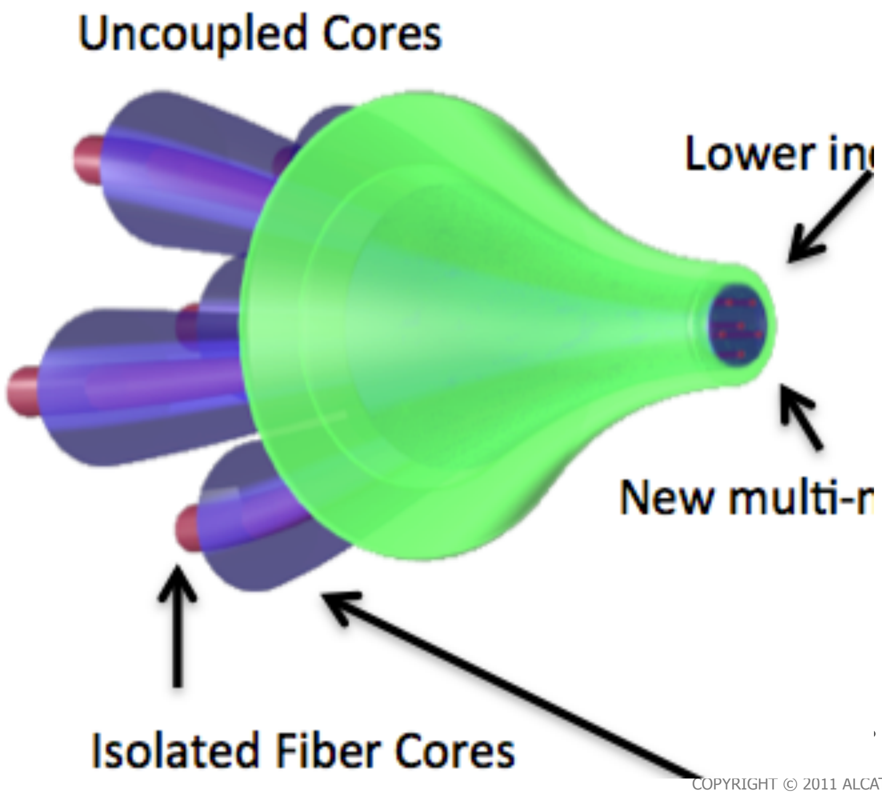
SINGLE CORE MIMO-BASED TRANSMISSION

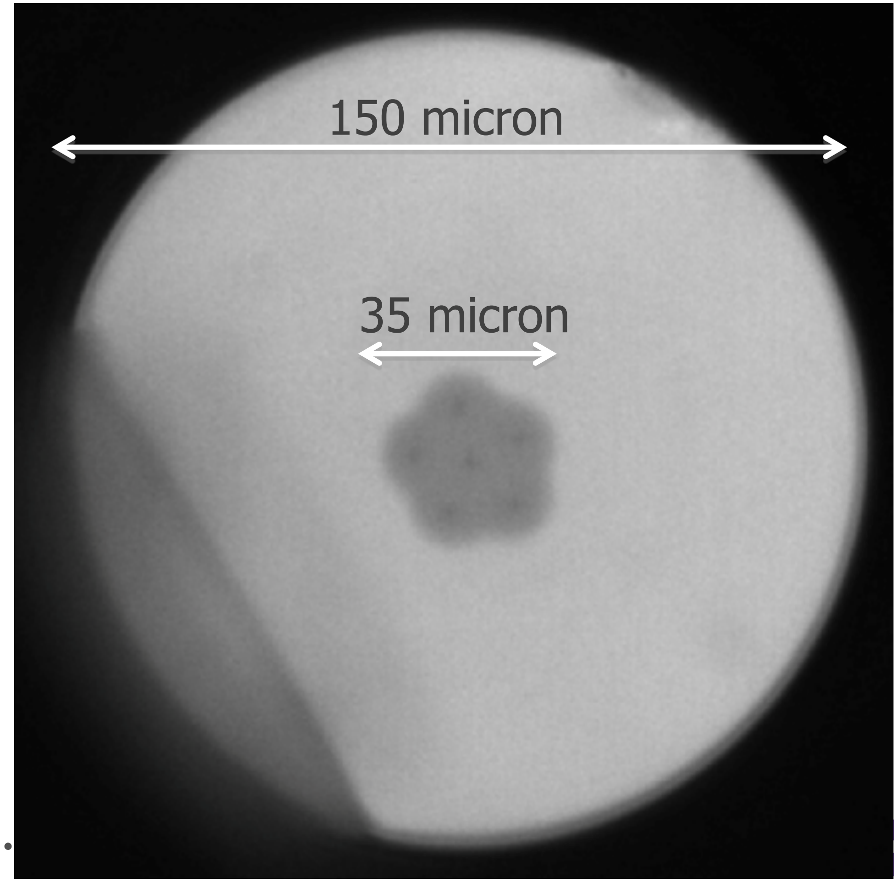


Output Pattern of Lanterns

Scrambled Modes!!!

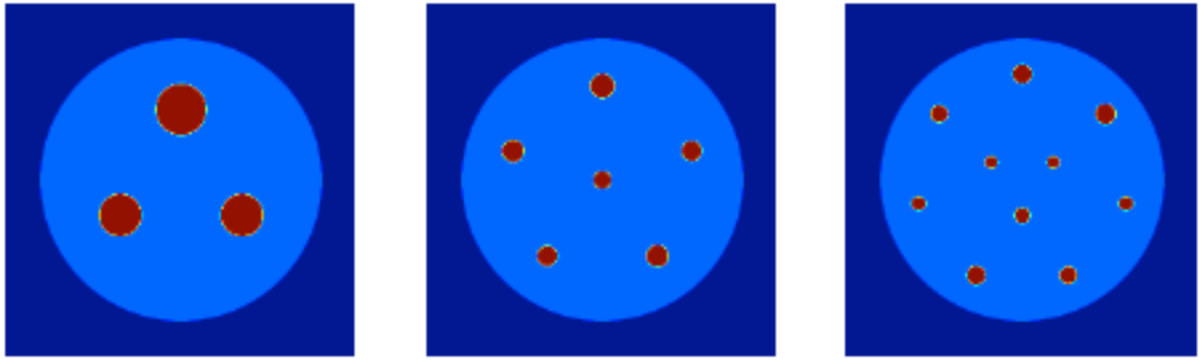






DISSIMILAR FIBER PHOTONIC LANTERNS

- ❑ Core diameter.

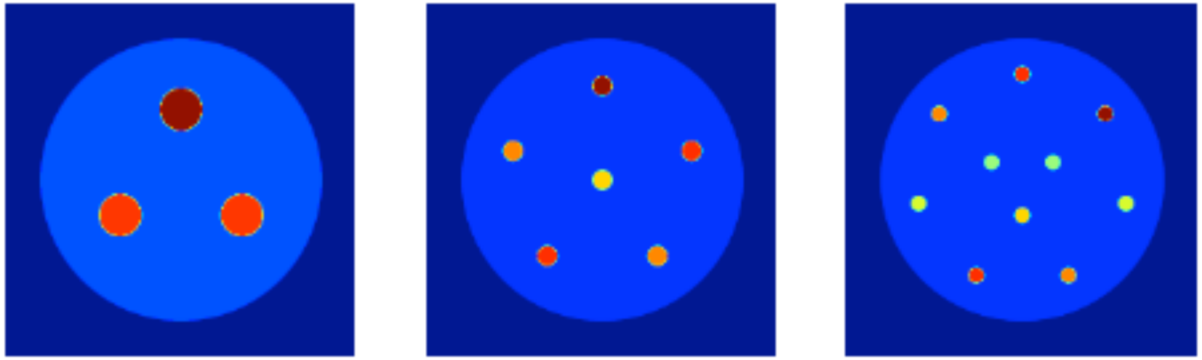


3 Modes
2 Groups

6 Modes
3 Groups

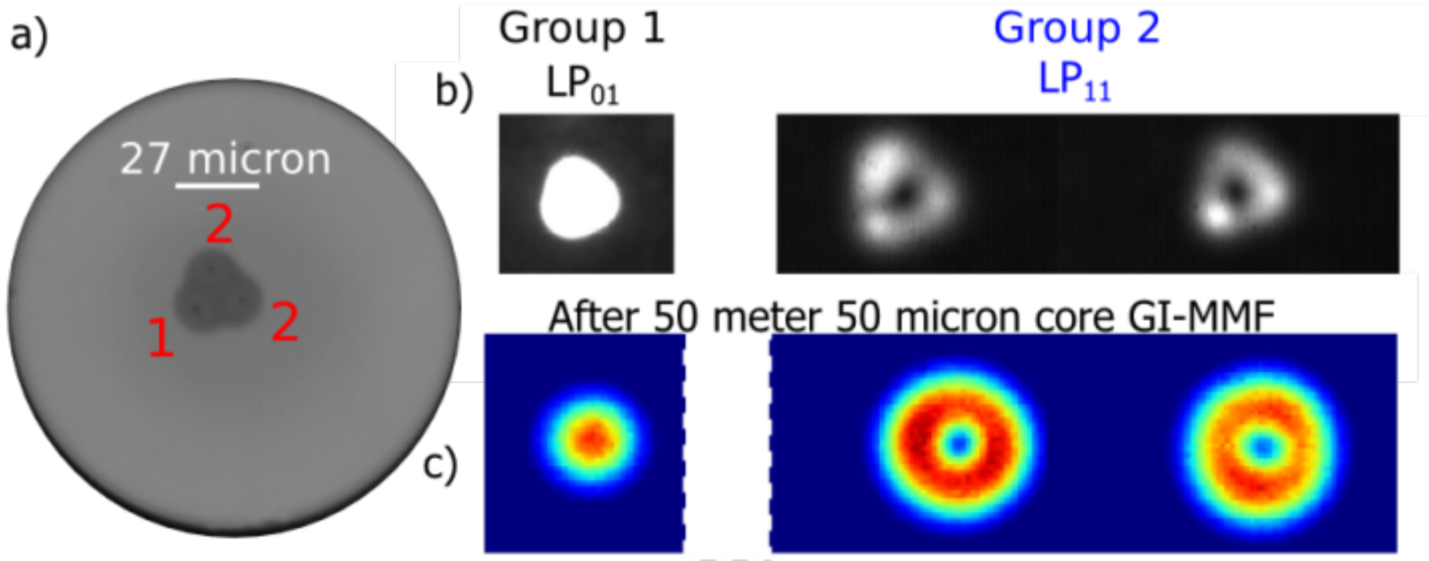
10 Modes
4 Groups

- ❑ Core doping.



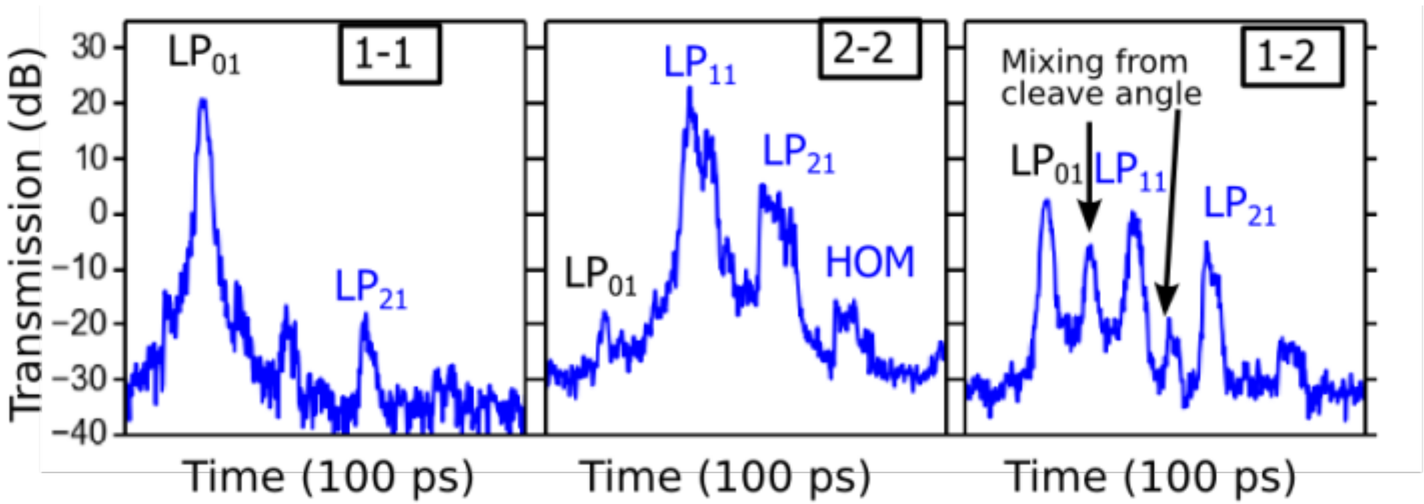
Fibers have mode-groups, each with degenerate groups.
Within each mode-group, there is strong mode-mixing.
Multiplexing into degenerate groups reduces adiabaticity requirement.

MODE SELECTIVE PHOTONIC LANTERNS (3 MODES)

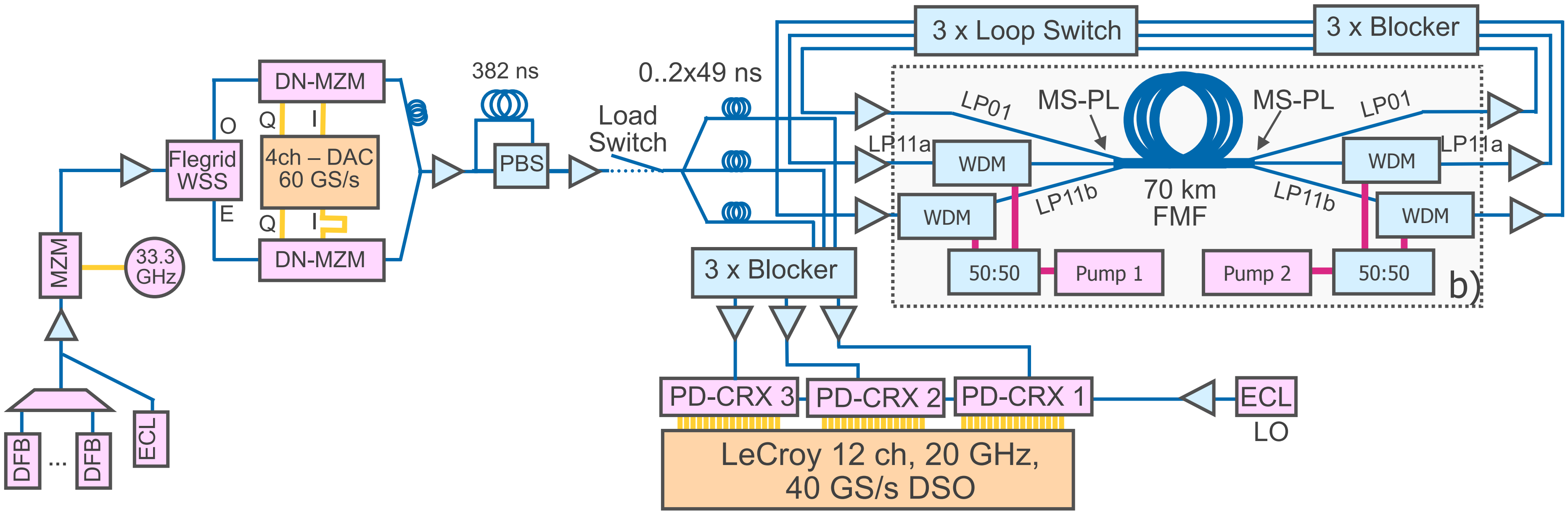


Loss (into fiber):
0.2dB for LP01
0.4dB for LP11a/b

Element of the transmission matrix after reflection by end cleave of 50 m MMF fiber



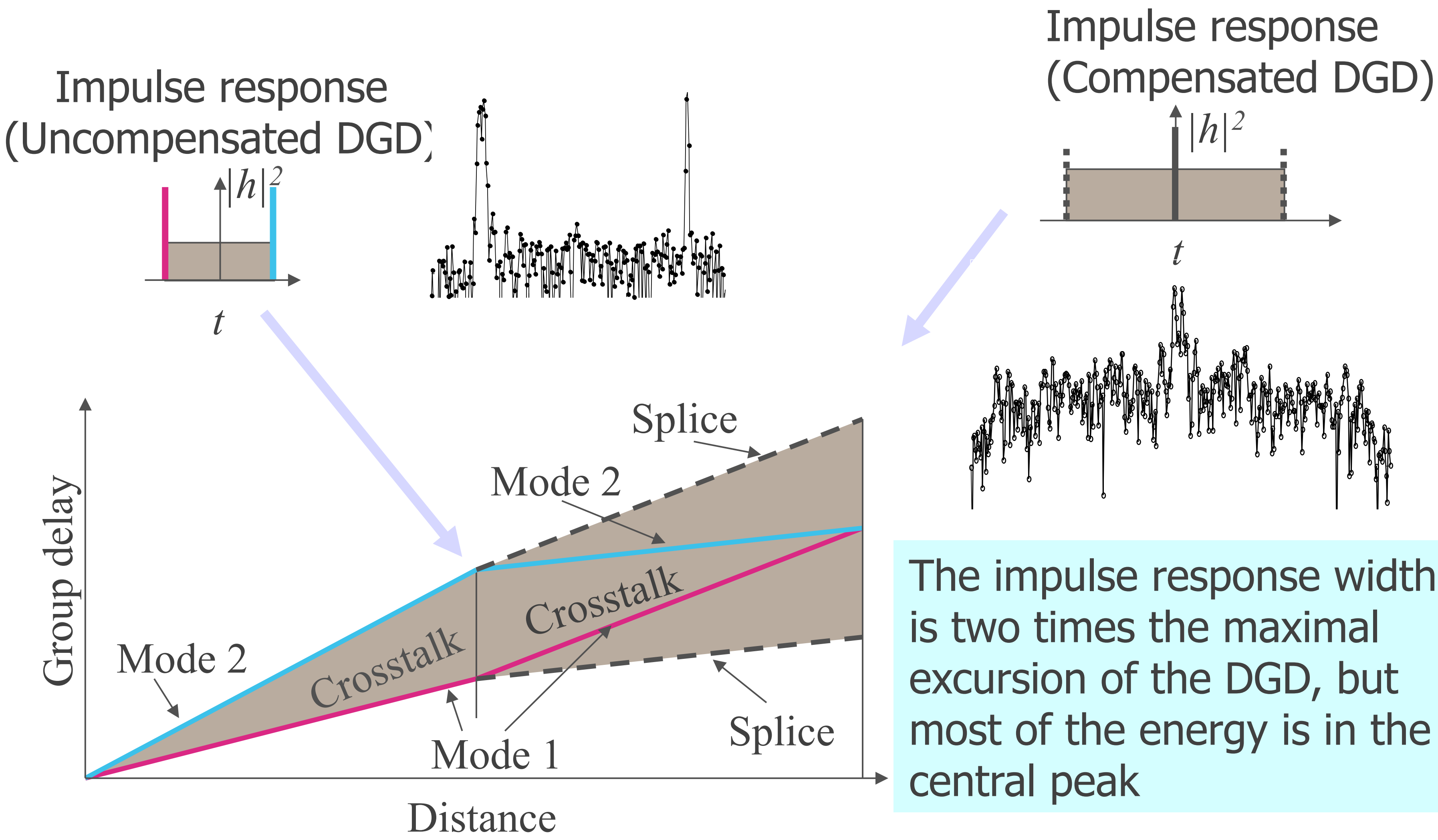
TRANSMISSION SETUP TRANSPARENT RAMAN PUMPED SPAN



Blocker where optimized to equalize the spectral dependence of the Raman gain

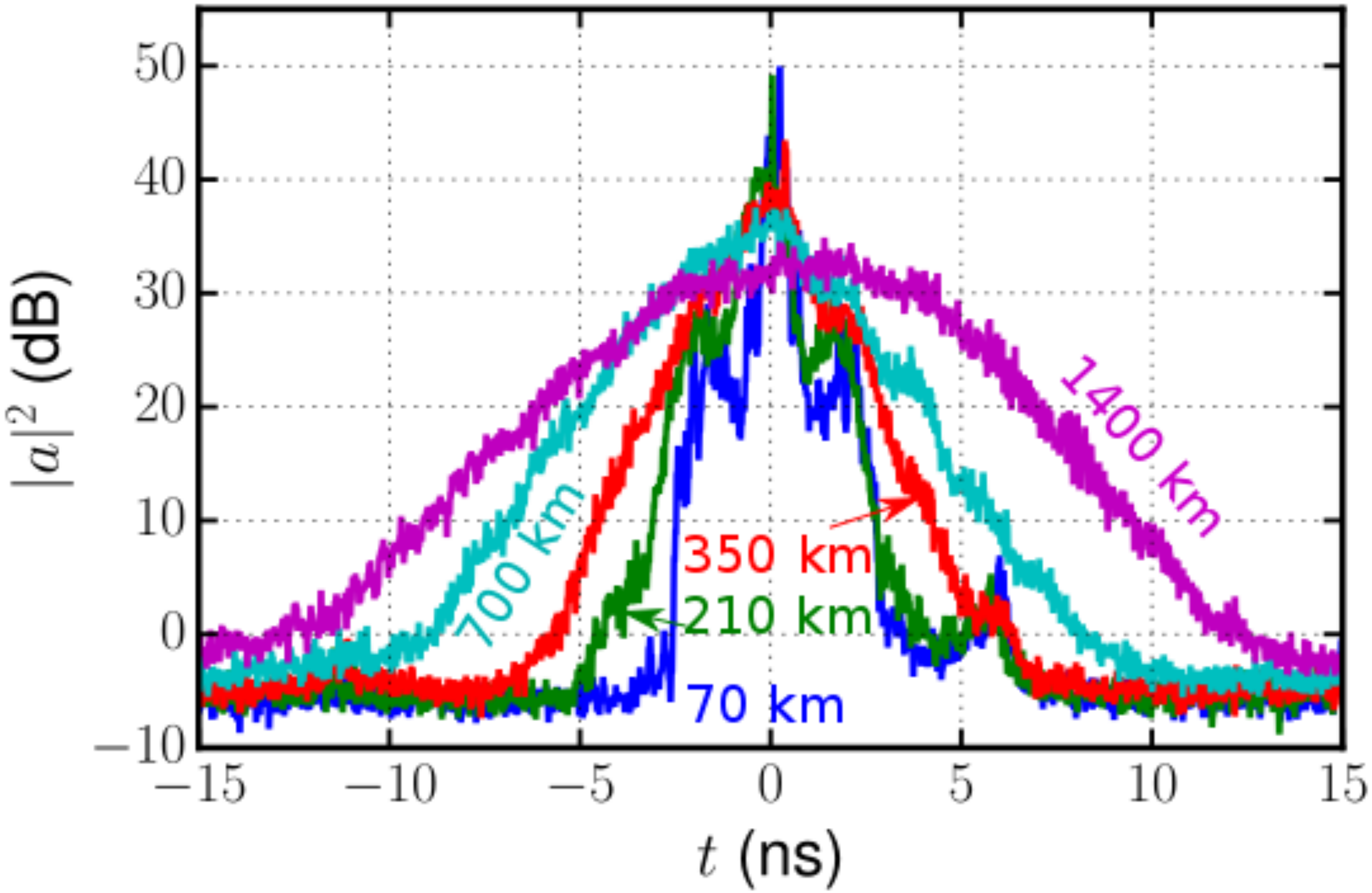
Alcatel·Lucent

IMPULSE RESPONSE OF DGD COMPENSATED SPAN
MODE MULTIPLEXERS



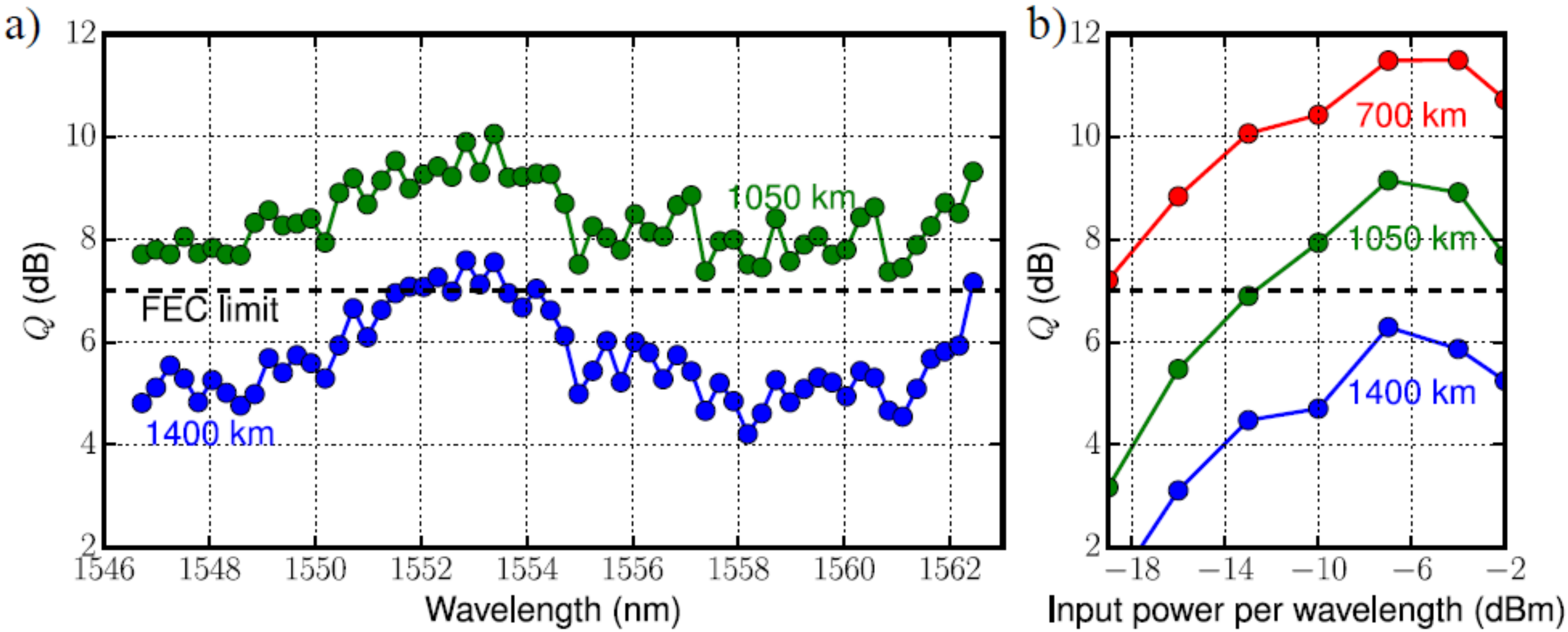
The impulse response width is two times the maximal excursion of the DGD, but most of the energy is in the central peak

IMPULSE RESPONSE OF THE 215km 3-MODE SPAN



- Impulse response is well compensated and can be cascaded 20 or more times

TRANSMISSION RESULTS



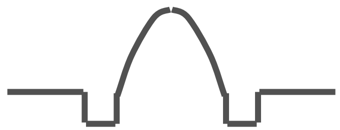
R.Ryf et al., ECOC 2015

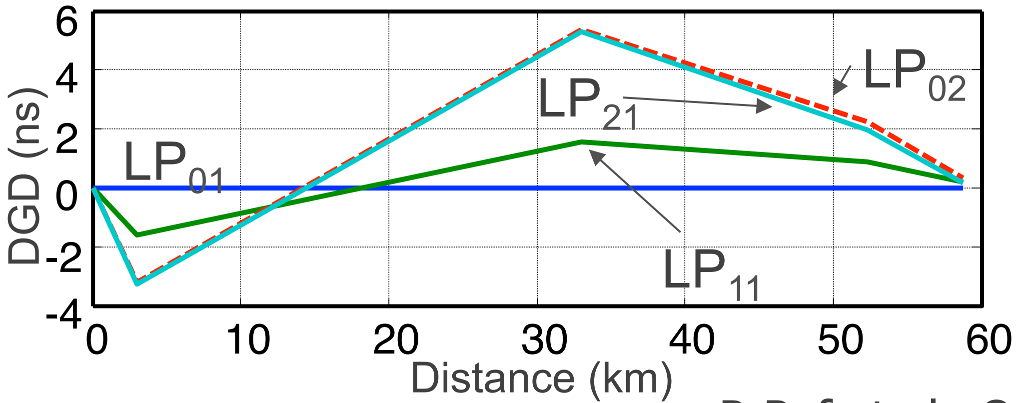
- 60 * 6 * 30 Gbaud QPSK / 1.2 = 18 Tbit/s over 2 THz bandwidth
- Spectral efficiency 9 bit/s/Hz
- Spectral efficiency distance product 9450 bit/s/Hz km

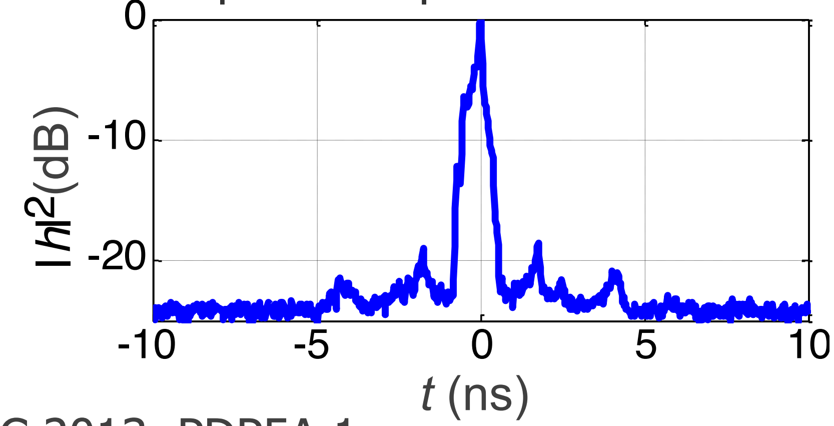
Alcatel·Lucent

GRADED INDEX FIBER SUPPORTING 6 SPATIAL MODES
DGD COMPENSATED FIBER

- Graded index profile designed to minimize DGD across all modes
- The effective area of the FMF was 90 µm^2 for LP_{01} and LP_{11}, 120 µm^2 for LP_{21}, and 180 µm^2 for the LP_{02} mode.
- The loss is around 0.2 dB/km for the LP_{01} mode
- The chromatic dispersion was 18 ps/(nm km)
- DGD of the compensated span:





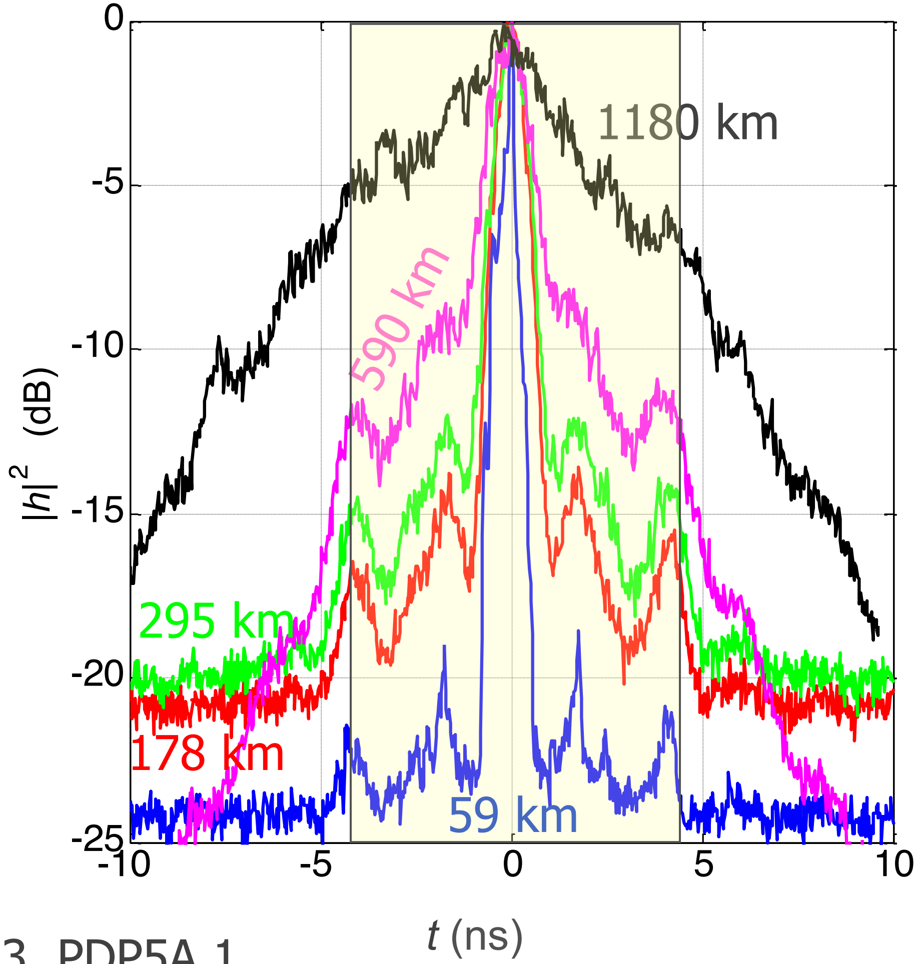


R.Ryf et al., OFC 2013, PDP5A.1

IMPULSE RESPONSE OF THE 6-MODE FMF

After 59, 178, 295, 590, and 1180 km

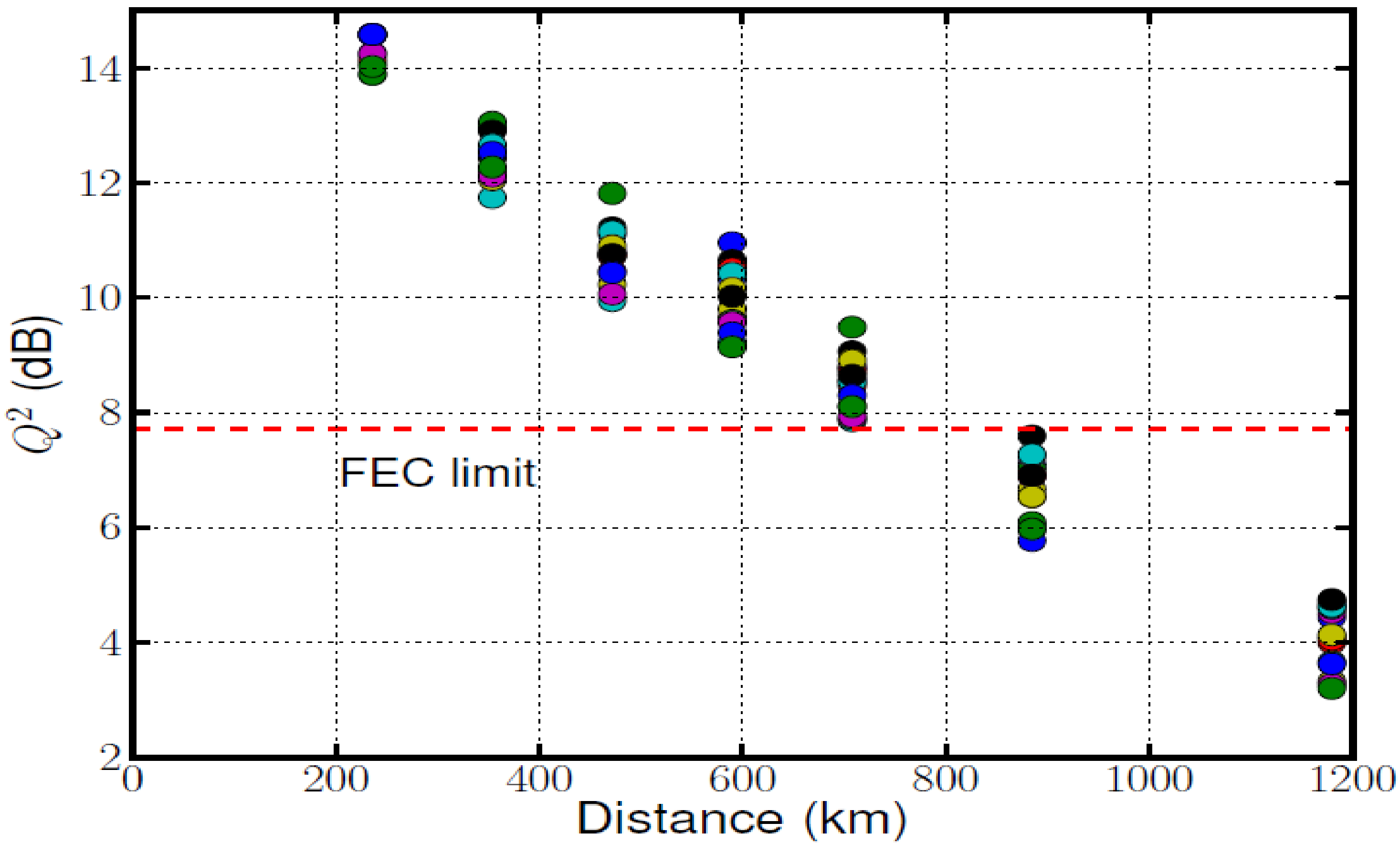
- Impulse response is obtained based on a channel estimation
- All the 144 impulse responses are qualitatively similar
- We show impulse responses obtained by averaging the intensities of all 144 individual impulse responses
- The total width stay is bounded by the max DGD excursion of 8.2 ns up to 700km



R.Ryf et al., OFC 2013, PDP5A.1

Alcatel·Lucent

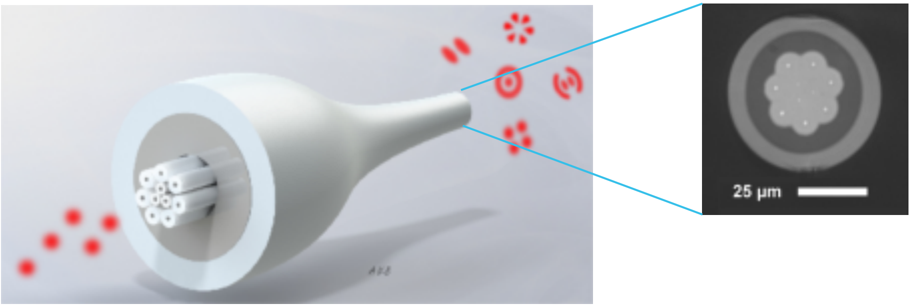
Q-FACTOR FOR 12 x 12 MIMO TRANSMISSION
59 km FMF SPAN AND 20-Gbaud QPSK SIGNALS



- All 32 WDM channels above FEC limit after 708 km transmission
- Spectral efficiency of 32 b/s/Hz for 16QAM format

Alcatel·Lucent

10-MODE MODE-SELECTIVE PHOTONIC LANTERN

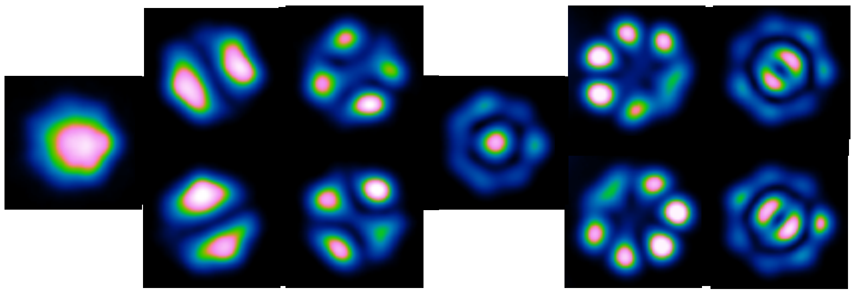


Core diameter = 27 µm

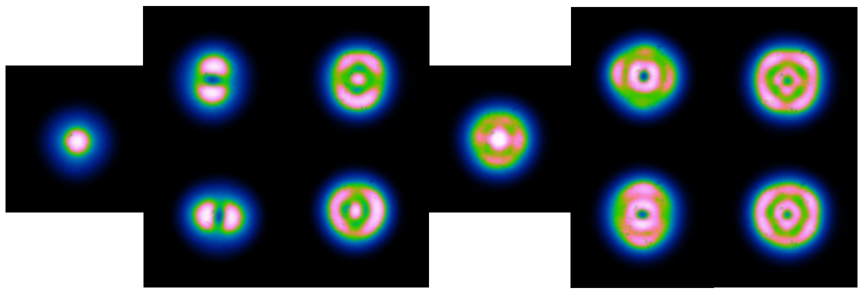
Spliced to 10-mode GI fiber

LP mode	LP_{01}	2 × LP_{11}	2 × LP_{21}	LP_{02}	2 × LP_{31}	2 × LP_{12}
Fibre core diameter [µm]	23	20	15	9	13	6.5
Mode dependent losses [dB]	0.25	0.3	0.7	0.75	1.25	2.2

Lantern output

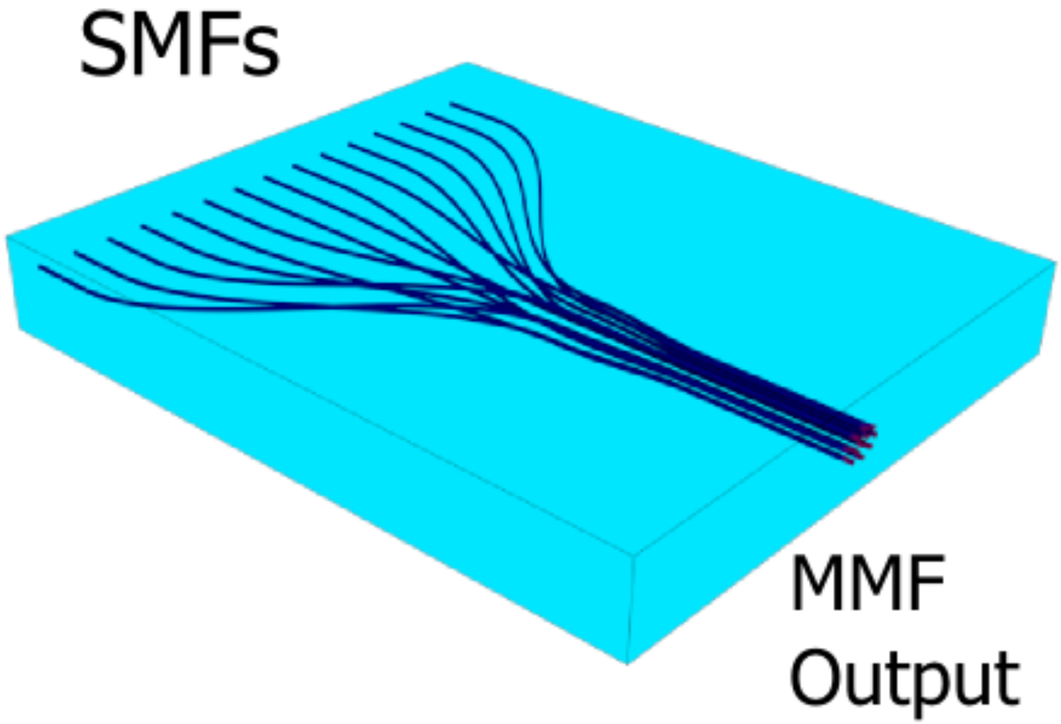


10-mode fiber output

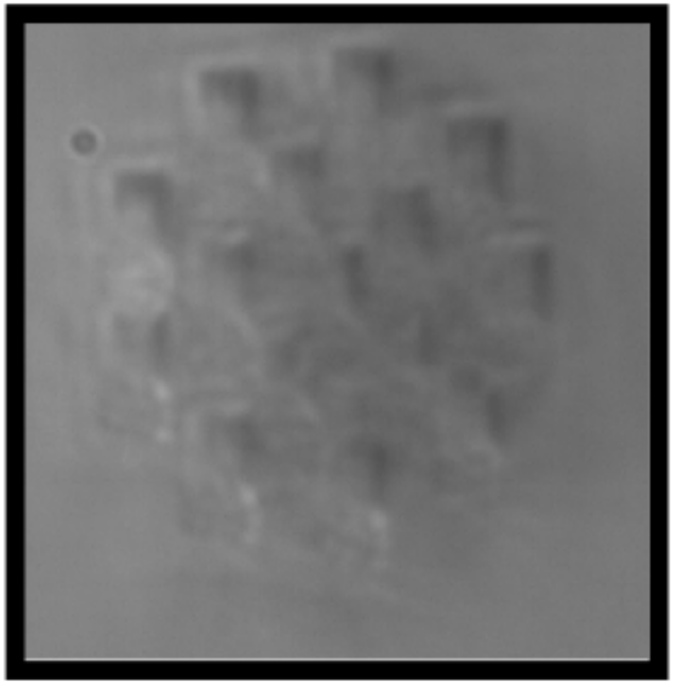


Alcatel·Lucent

3D WAVEGUIDE PHOTONIC LANTERNS TO COUPLE INTO
15-MODE MULTIMODE FIBER



48 µm core

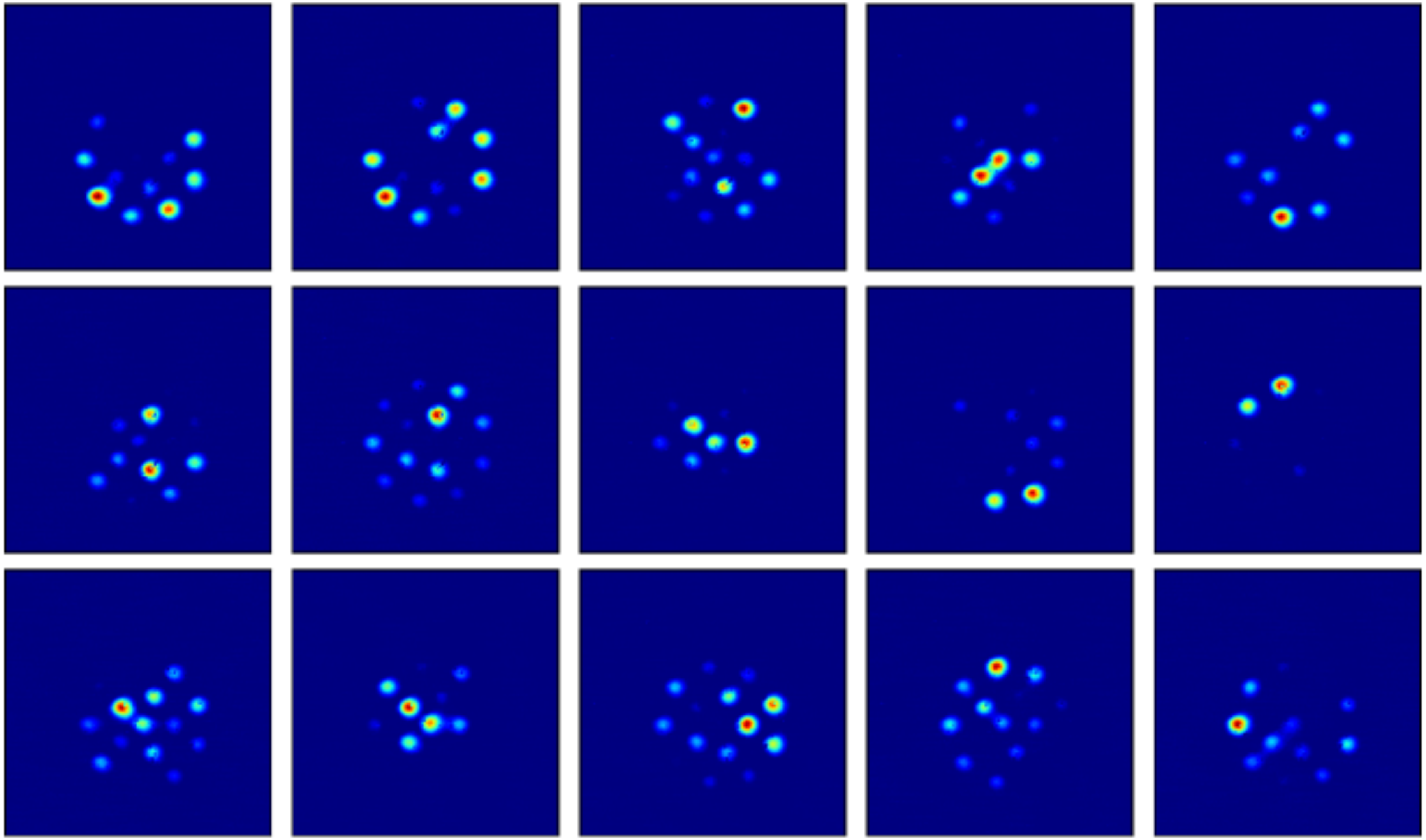


Coupled core approximates a multi-mode core.
Requires 2x demagnification for coupling to the 9-LP mode MMF.

Fontaine et.al. OFC 2015 PD Th5C.1

Fabricated by UC Davis

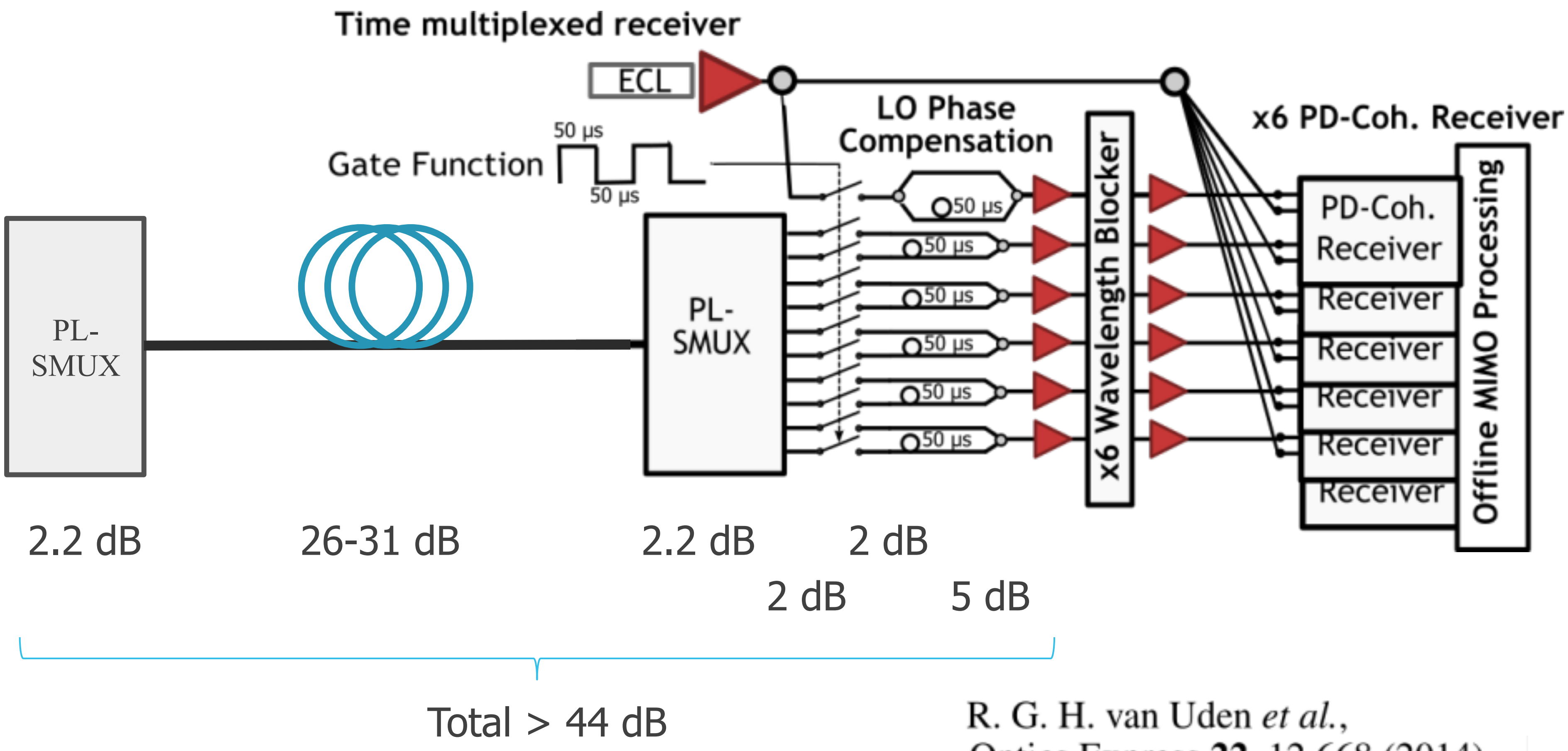
OUPUT PROFILES OF 15-MODE 3D WAVEGUIDE



5-7 dB Insertion loss, 6-7 dB MDL

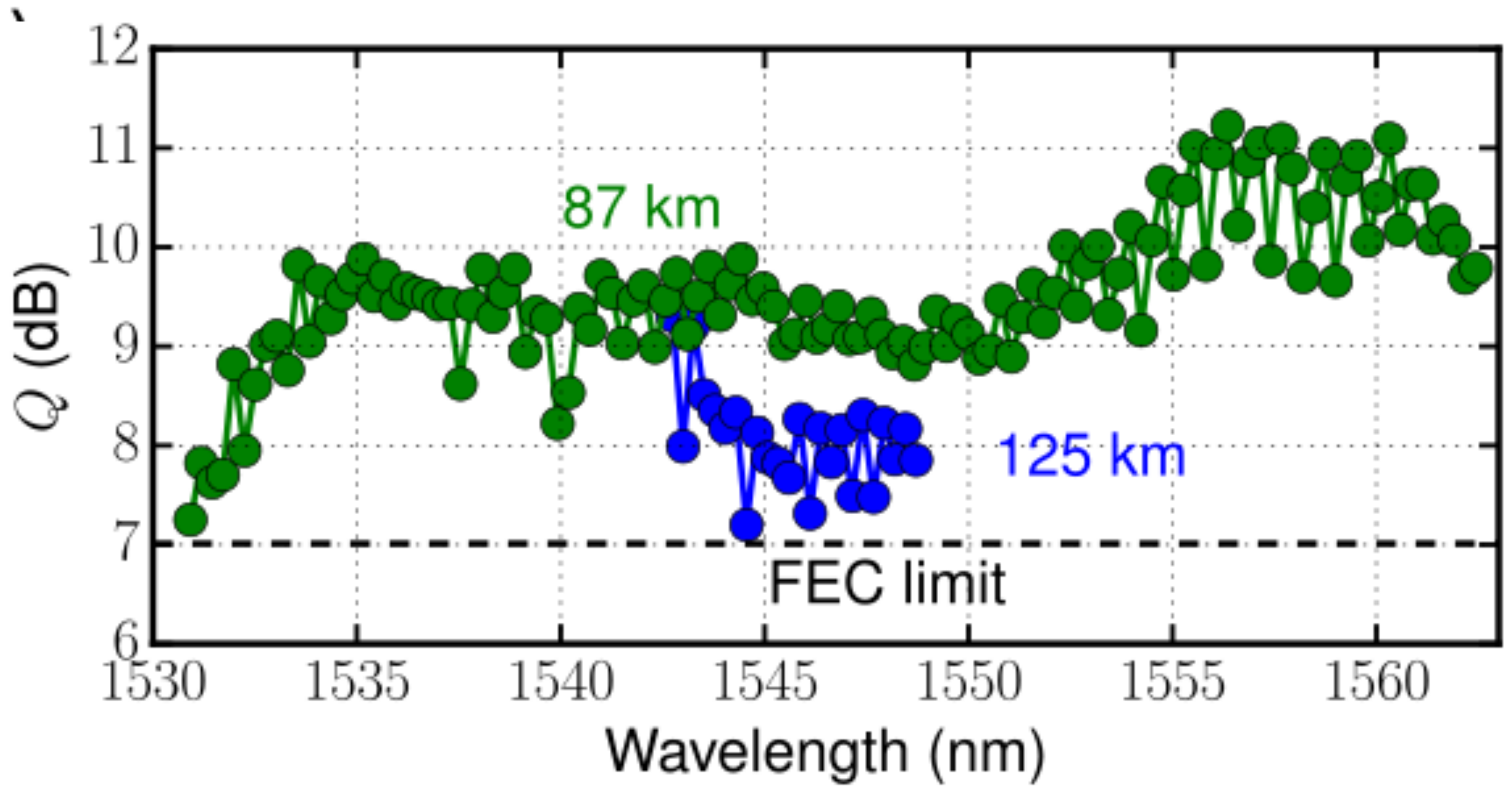
Fontaine et.al. OFC 2015 PD Th5C.1

RECEIVER SETUP – LOSS BUDGED



R. G. H. van Uden *et al.*,
Optics Express **22**, 12,668 (2014).

10 MODE TRANSMISSION RESULTS



Transmission distances up to 125 km can be achieved with 24 WDM channels (23.2 Tb/s) and 87 km for a full C-band signal with 120 WDM channels (**115.2 Tb/s**)

R.Ryf et al., ECOC 2015, PDP

Alcatel·Lucent

CONCLUSION

- We have demonstrated that high spectral-efficiency (up to 43 bit/s/Hz) high-performance transmission (up to 117 Tbit) is possible in numerous fibers supporting multiple spatial channels for distances up to 4200 km
- Key requirements for the fibers are:
  - Low mode dependent loss
  - Low differential group delay
- If modes are well separated, it is possible to use a subset of the modes

SUMMARY:MIMO BASED TRANSMISSION RESULTS

Fiber Type	Nr Spatial channels	Spectral Eff bit/s/Hz	Distance km	Spectral Eff . Distance bit/s/Hz.km	Reference
CC	6	18	1750	30690	R. Ryf ECOC 2014
CC	3	4	4200	16800	R. Ryf OFC 2012
FMF	6	16	708	11328	R. Ryf ECOC 2013
FMF	3	7.6	1000	7600	E. Ip OFC 2013
FMF	6	32	176	5632	R. Ryf OFC 2013
FMF	10	28.2	125	3600	R. Ryf ECOC 2015
MMF	3	9	305	2745	R. Ryf ECOC 2014
FMF	3	3	900	2700	R. Ryf OFC 2014
FMF	15	43.6	22.8	994	N. Fontaine OFC 2015
FMF-MC	3	20.6	40	824	T. Mizuno OFC 2014
FMF	6	10	74	740	Y. Chen, ECOC 2014
MMF	6	7	17	119	R. Ryf OFC 2014

*Spectral efficiency per coupled group

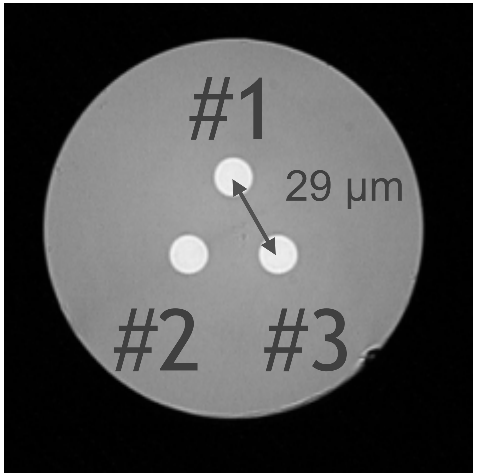
COUPLED CORE 3-CORE MULTI-CORE FIBER (MCF)
CHARACTERISTICS OF A 60 km 3-CORE FIBER

- In coupled-core multi-core fibers, cores are allowed to couple, and can therefore be placed closer than in uncoupled multi-core fiber
- MIMO DSP is required to undo the coupling
- Couple-core fiber show strong coupling which is beneficial to reduce the DGD build-up in long distance transmission

CHARACTERISTICS OF A 60 km 3-CORE FIBER

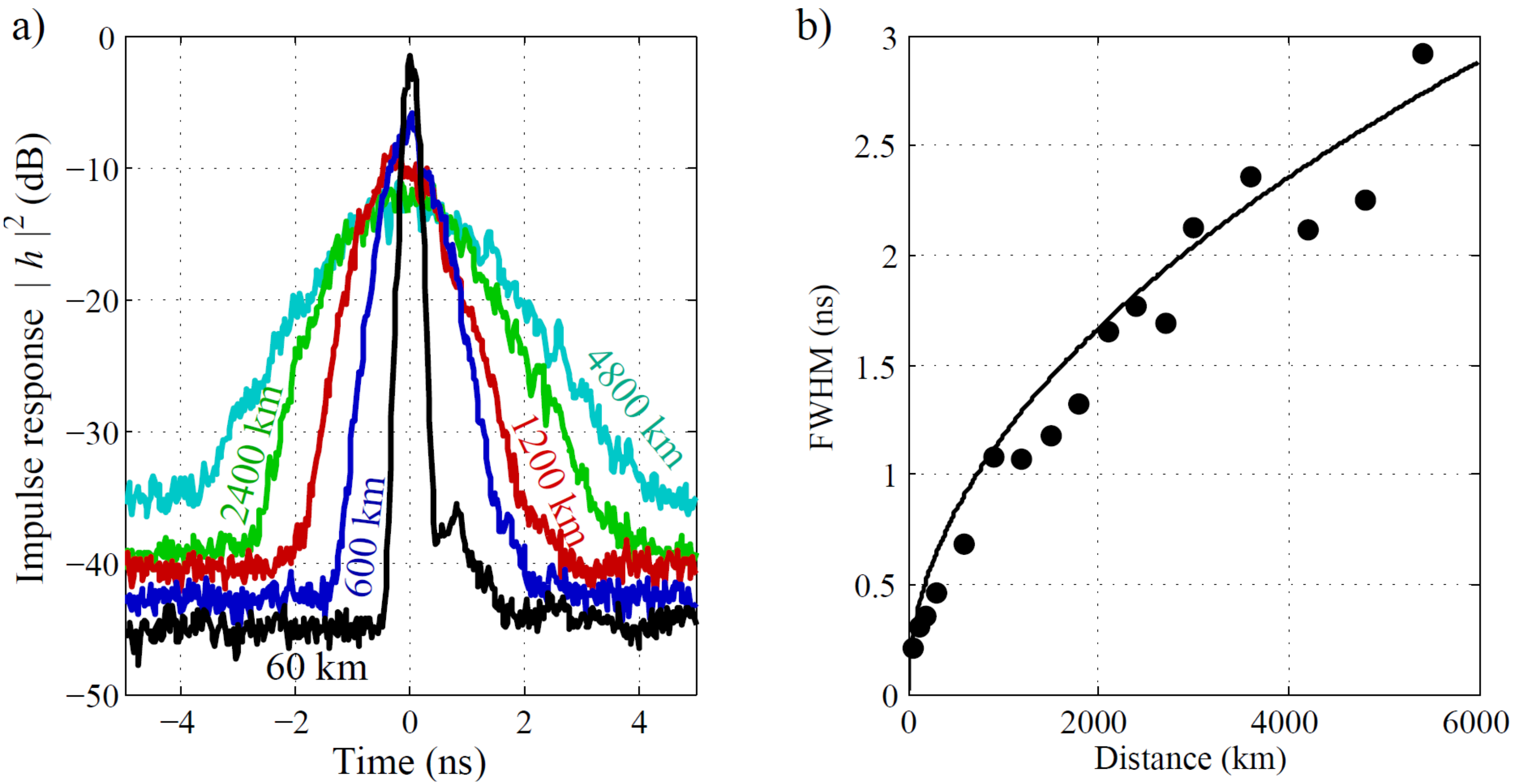
- Core diameter is 12.4 μm
- Refractive index step Δ = 0.27%
- Distance between cores 29.4 μm
- Effective core area 129±2 μm^2
- Attenuation 0.181 dB/km
- Dispersion 20.6 ps/nm/km
- Dispersion slope 0.06 ps/nm^2/km
- Super-mode DGD 224 ps/km

3-CORE MCF



R. Ryf et.al. PDP ECOC 2011

IMPULSE RESPONSE AS FUNCTION OF THE DISTANCE



- FWHM Pulse width after 60 km is 230 ps

R.Ryf et al., OFC 2012, PDP5C.2

- Pulse width growths proportional to square root of distance