Spiral Launch Method for Enhanced MMF Bandwidth

D. Vernooy and H. Blauvelt

Xponent Photonics

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hblauvelt@xponentinc.com

Outline

I. Overview of the problem and proposed solution
- Overlap of various multimode fiber modes to center and outer index defects
- Launched mode populations for conventional offset launch (OSL) and spiral launch (SL)
- Encircled flux characteristics of offset and spiral launch

II. Bandwidth simulations for offset launch and spiral launches
- Fibers with single index defect
- Fibers with combinations of index defects

III. Simulation of impact of misaligned connectors on offset and spiral launch

IV. Implementation methods for spiral launch

V. Initial test results with spiral launch mode conditioning patchcord and comparison to offset launch and overfilled launch (OFL)

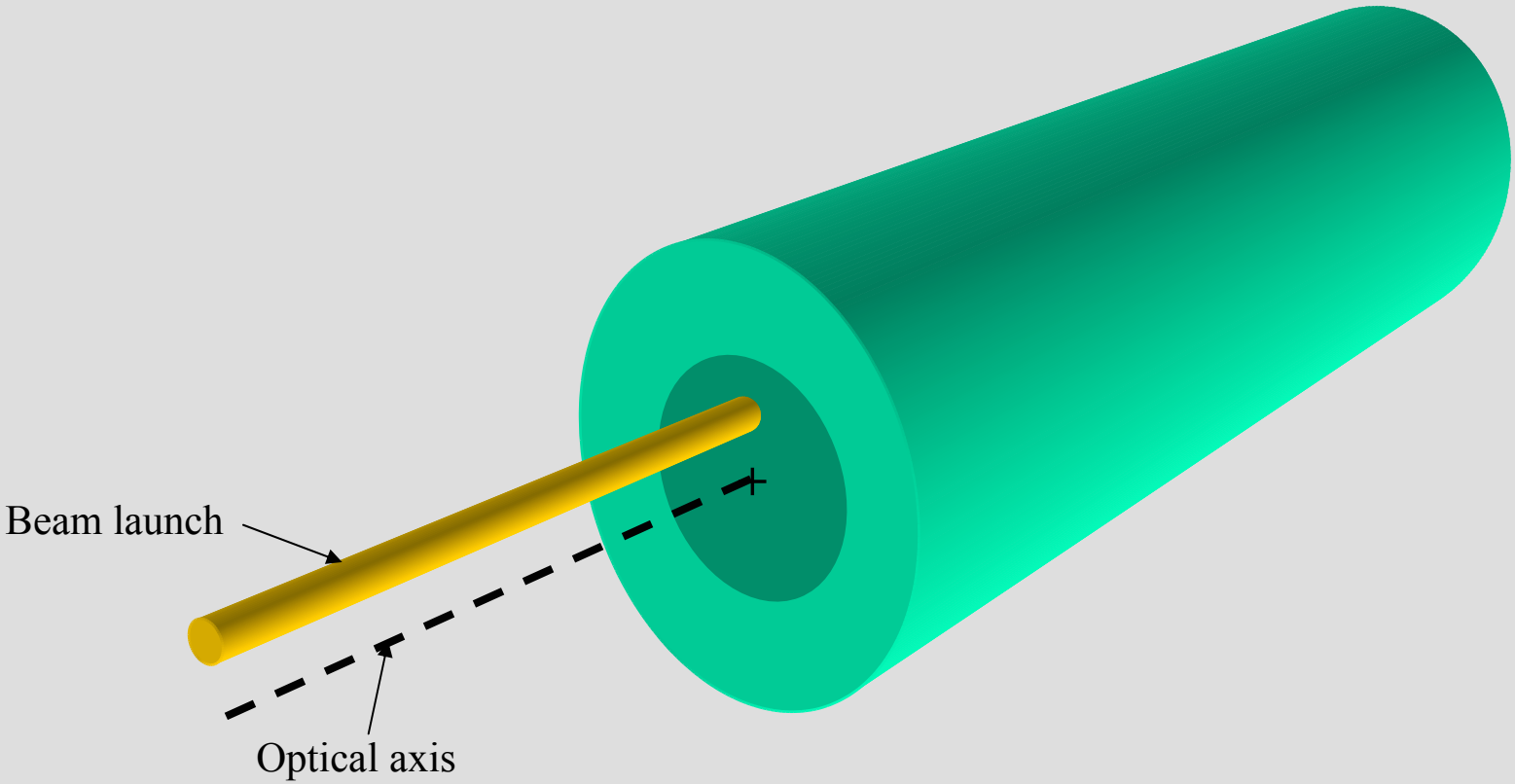
VI. Summary

I. Overview of Modal Dispersion Problem and Proposed Solution

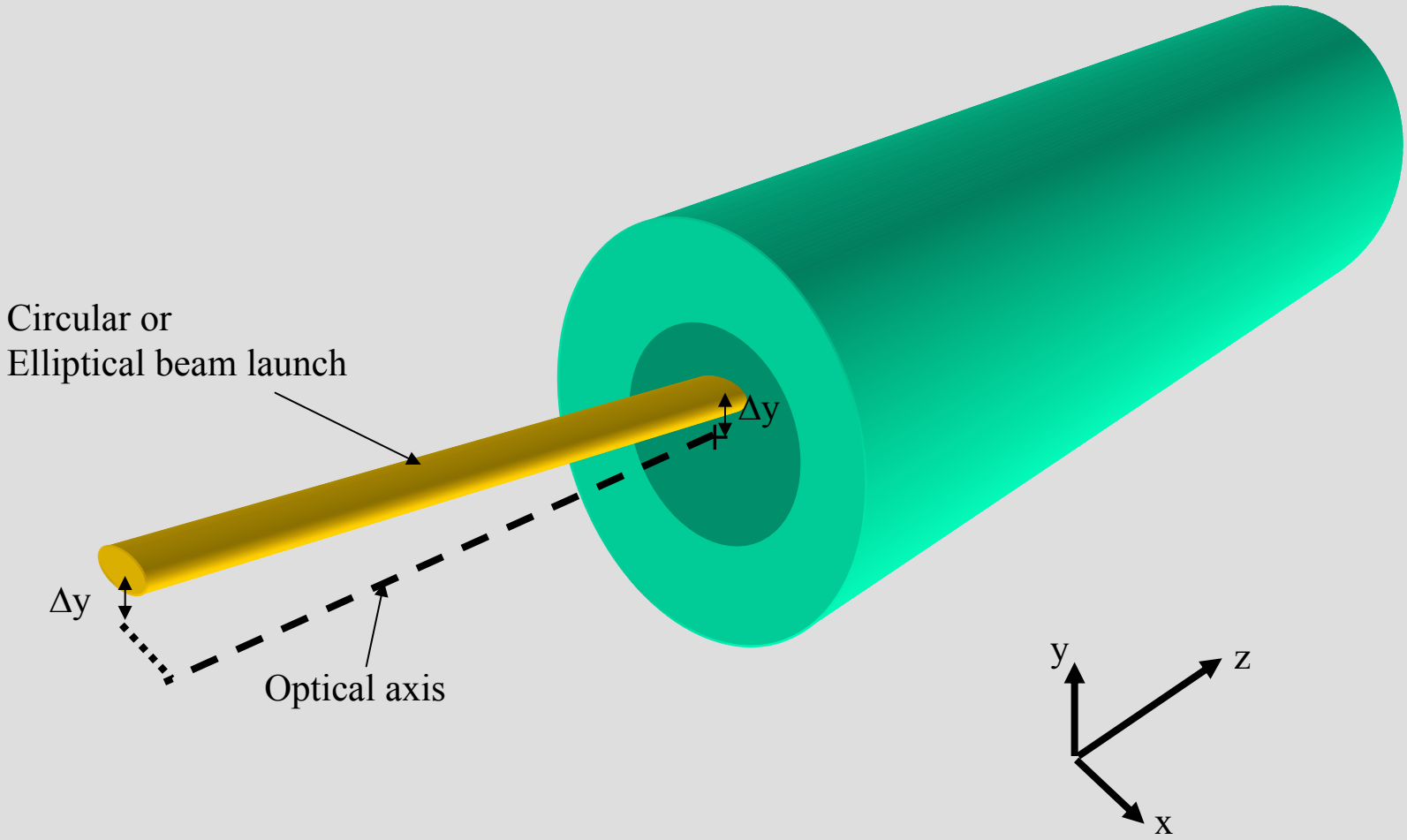
Offset vs Spiral Launch

- In offset launch, a beam (often from single mode fiber) is launched into MMF at a point that is radially offset from the center of the core. Beam is launched parallel to optical axis
- From a ray optics perspective, offset launch excites rays that periodically cross the center of the fiber with outer turning points equal to the initial radial offset
- In a spiral launch a beam is launched into the MMF with a radial offset and an angle in the azimuthal direction
- From a ray perspective, spiral launch excites rays that travel in a spiral path down the fiber and never cross the center of the core.

Conventional Offset Launch



Spiral Launch



Differential Mode Delay (DMD) Limited Bandwidth and Enhancement via Selective Mode Launch

- **Deviations from optimum index profile can significantly increase DMD and decrease bandwidth**
- **Three main categories of index profile defects**
  1. Dip or peak at center of core: Can be addressed by not launching modes that overlap the center of the core
  2. Dip or peak near core-cladding interface: Can be addressed by not launching modes that overlap the core-cladding interface.
  3. Deviation from optimum power law profile across core: Can be minimized by launching modes with a reduced range of principle mode numbers
- **Selective mode launch technique should address all three categories**
- **Conventional offset launch is very good at category 3, but not as good at simultaneously meeting categories 1 and 2**
- **Spiral launch can simultaneously minimize the impact from all three categories of index profile defect**

Overview of Mode Characteristics

- **Fibers have truncated power law index profile**

$$n^2 = n^2_{core}[1-2\Delta(r/a)^{\alpha}] \quad r<a$$
$$= n^2_{core}[1-2\Delta] \quad r>a$$

- **Modes can be characterized by an azimuthal mode number, L and a radial mode number, M; L=0, M=1 is fundamental mode**
- **For infinite quadratic profile, mode field has dependence**

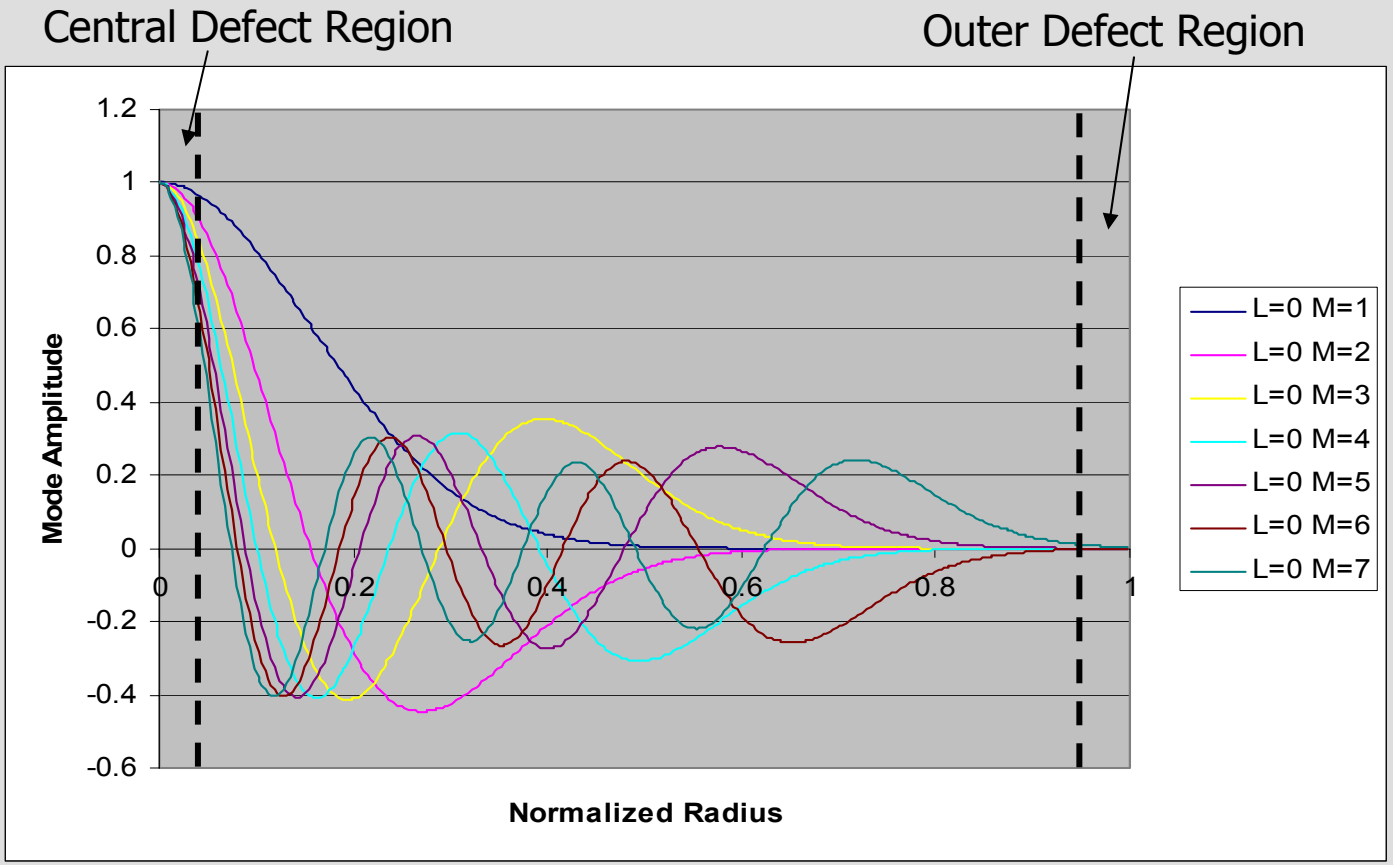
$$E \sim r^L L^L_{M-1}(Vr^2)\exp(-Vr^2/2)\exp(iL\Phi)$$

  - All modes of order L>0 have nulls in amplitude at center, exclusion from center increases with L
  - All L=0 modes have maximum amplitude at the center
  - Radial “center of mass” depends on principle mode number, m

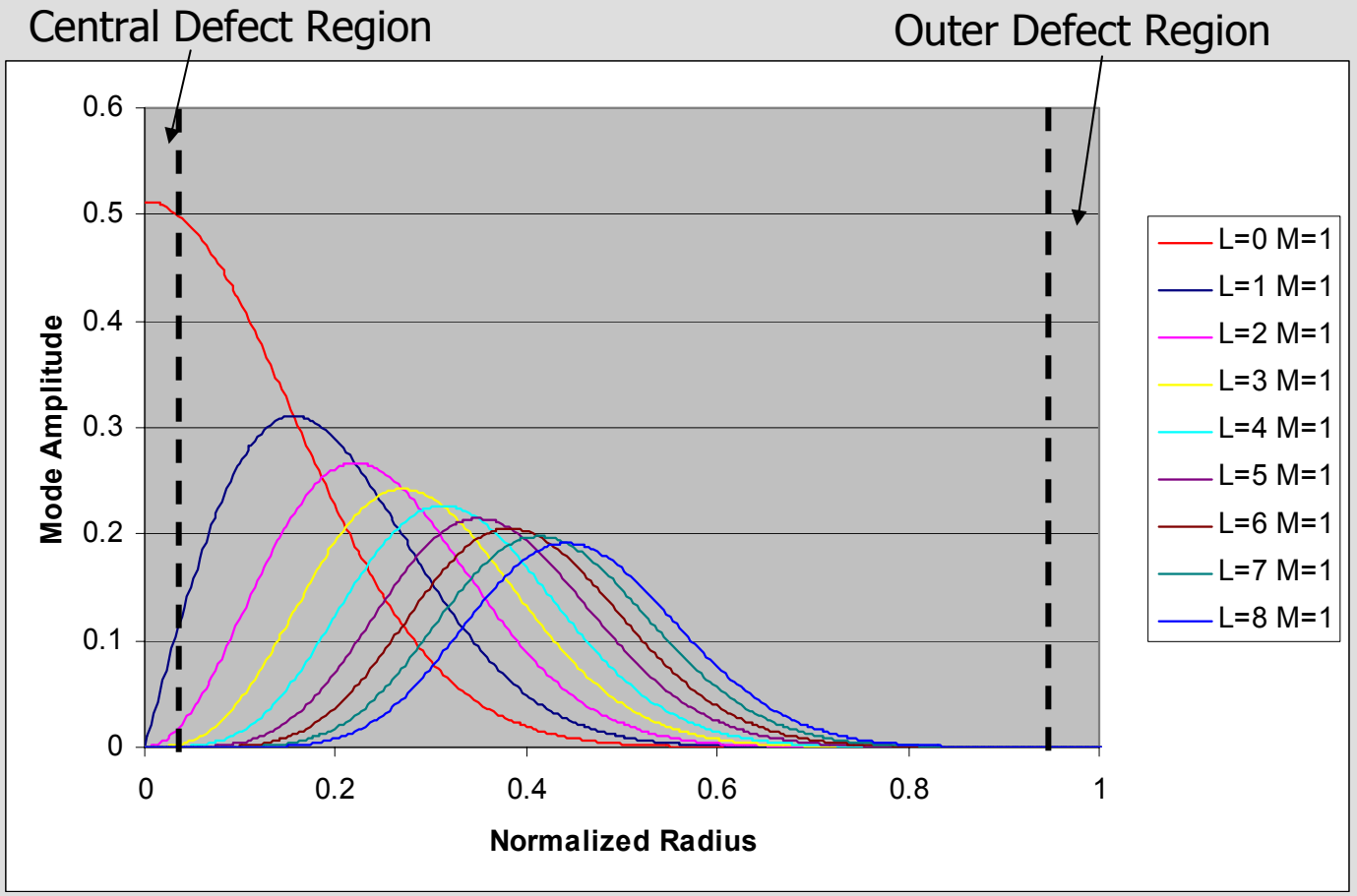
$$m = 2M+|L| - 1$$

- **Real multimode fiber modes are very similar except for modes approaching cut-off**

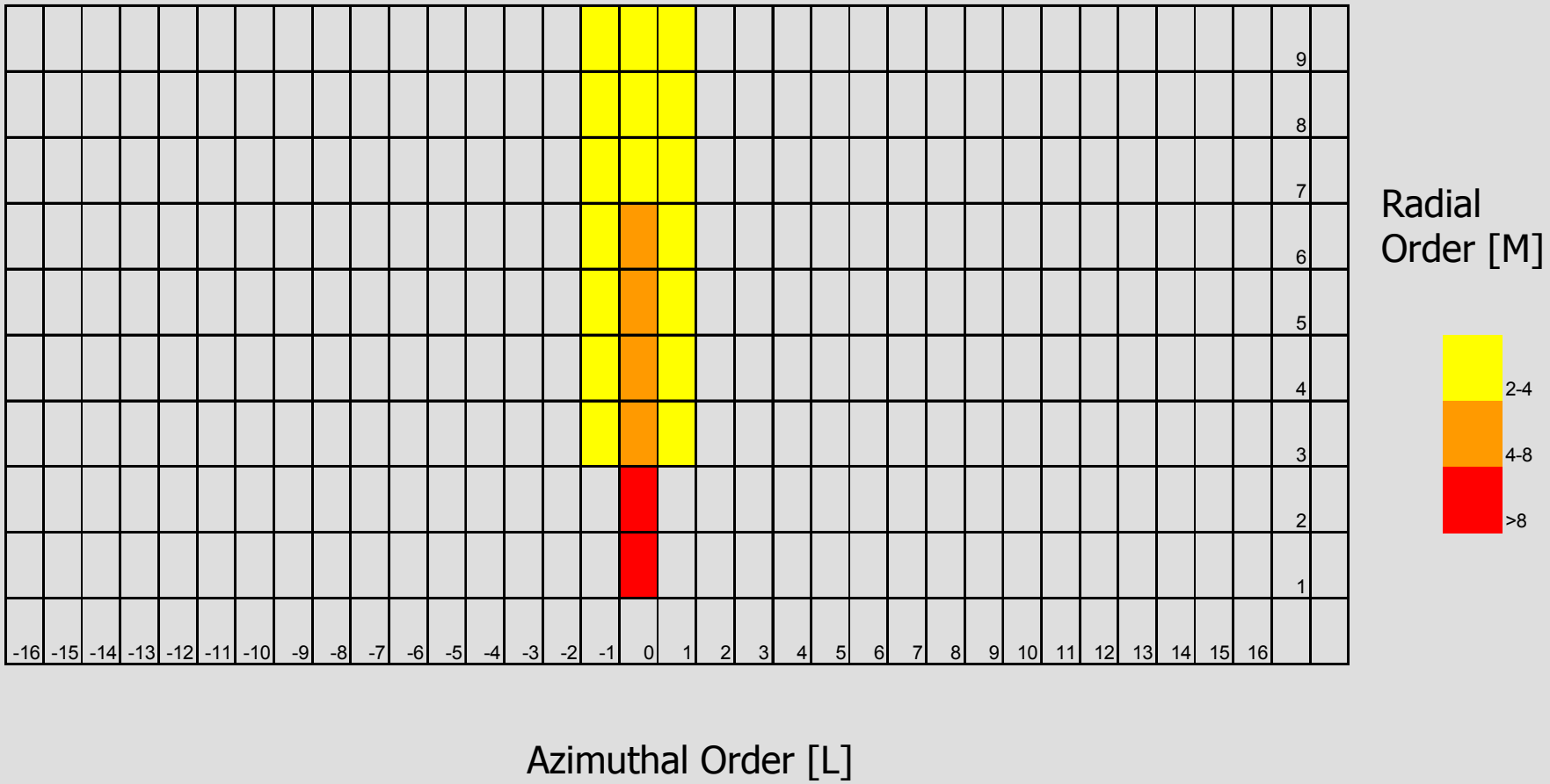
Lowest Azimuthal Order Modes: 62.5 Micron Fiber



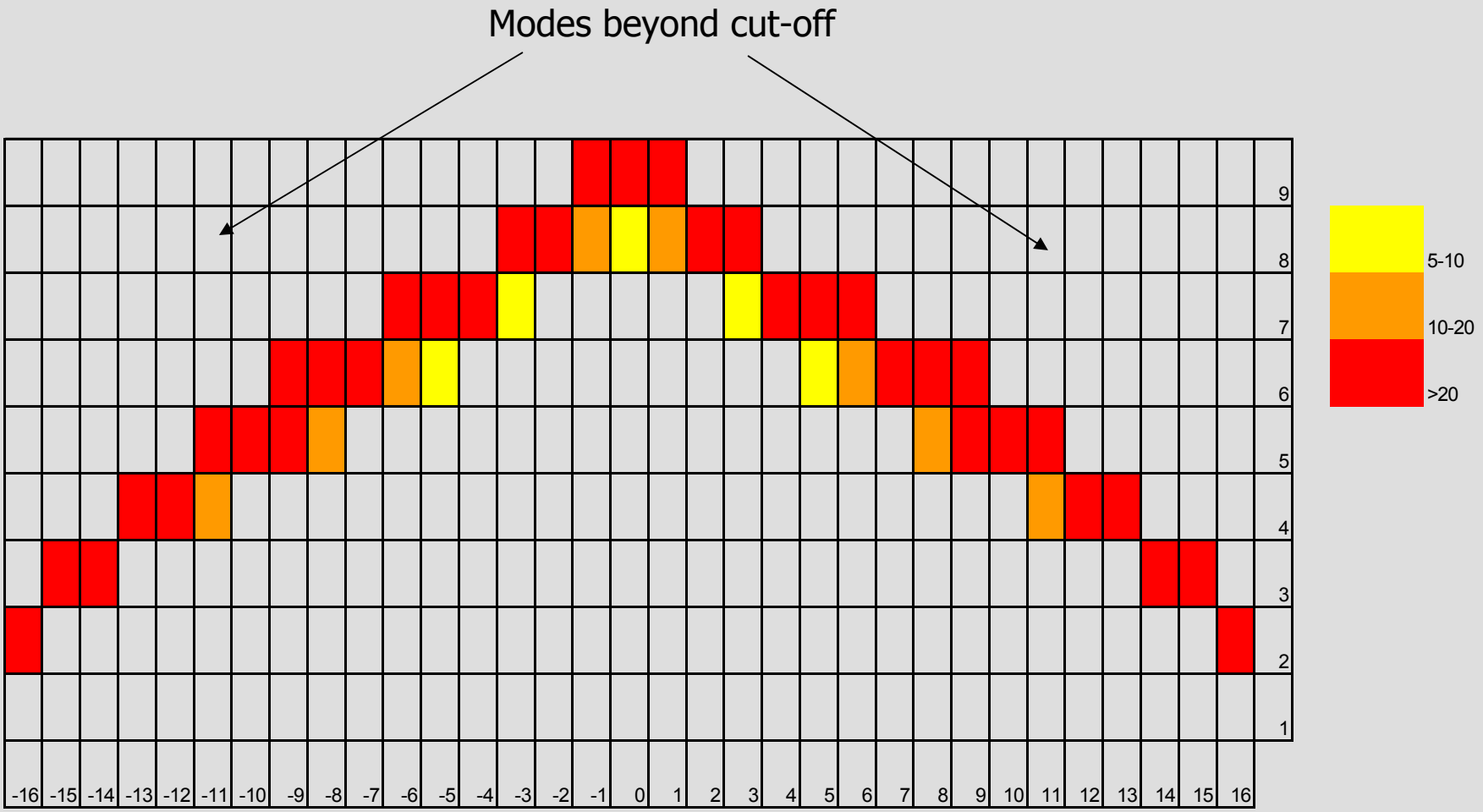
Lowest Radial Order Modes: 62.5 Micron Fiber



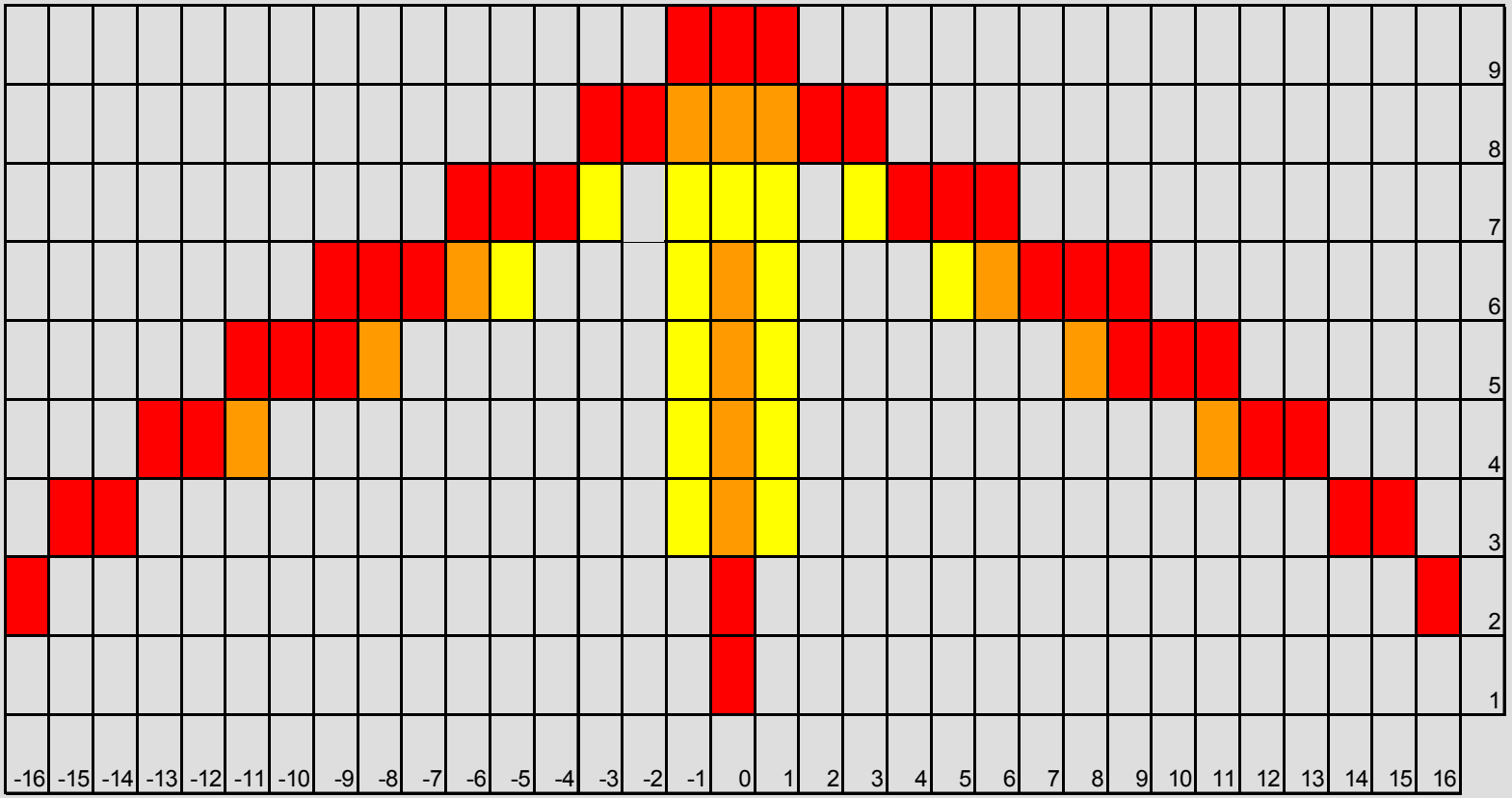
Mode overlap to Central Defect: 62.5 Micron Fiber



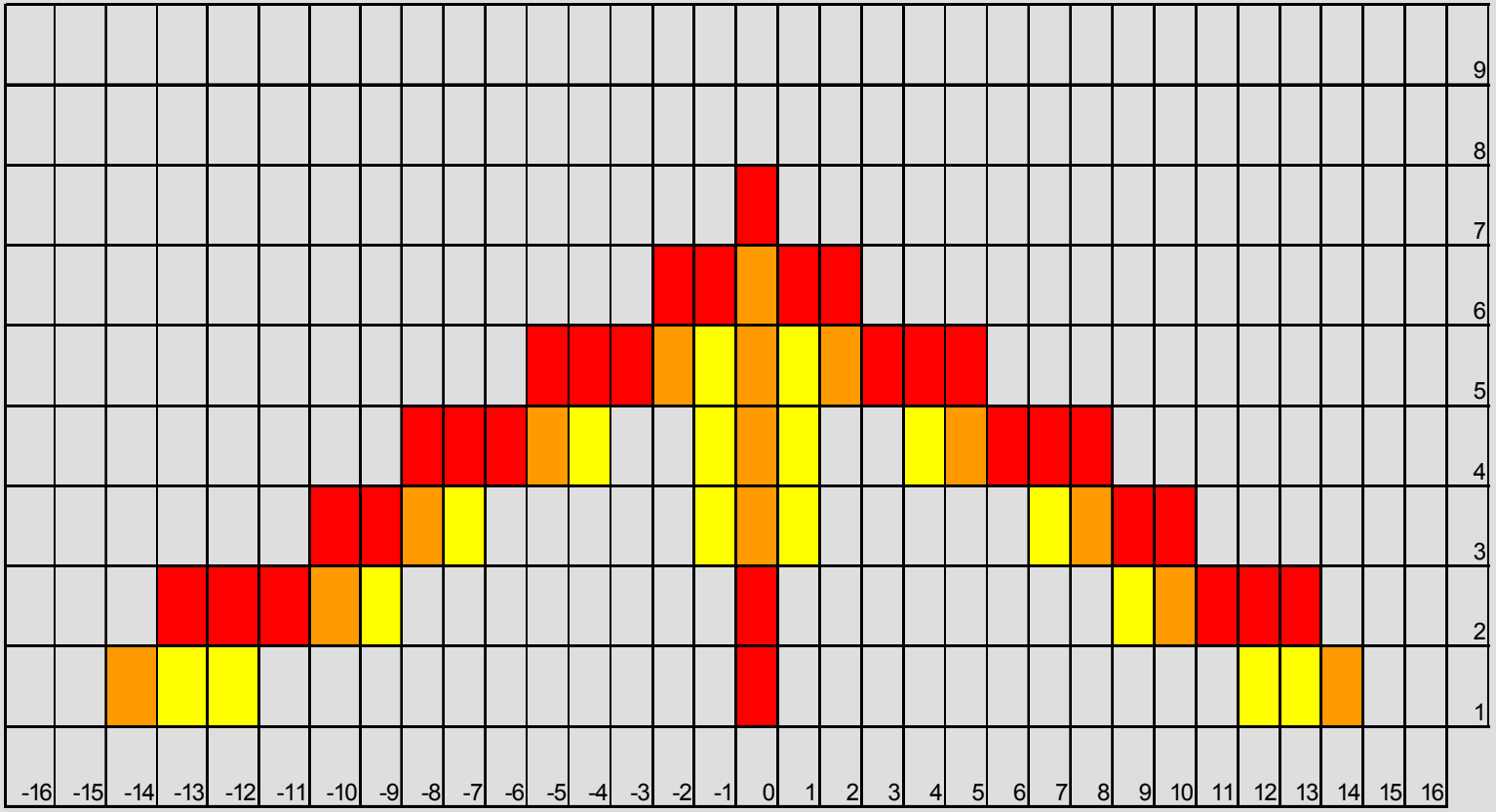
Mode Overlap to Outer Defect Region: 62.5 Micron Fiber



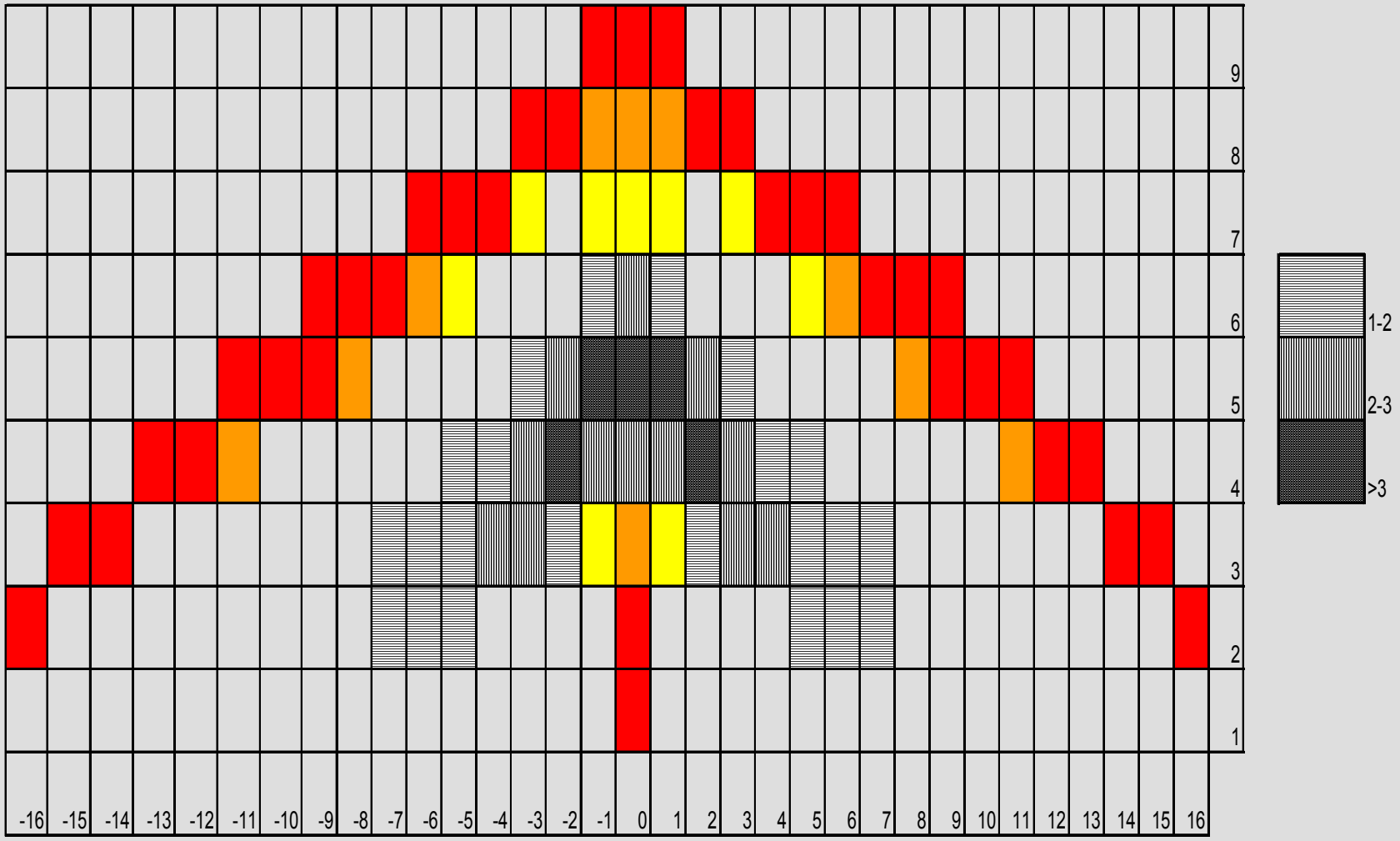
Combined Center and Outer Defect Exclusion Zone: 62.5 Micron Fiber



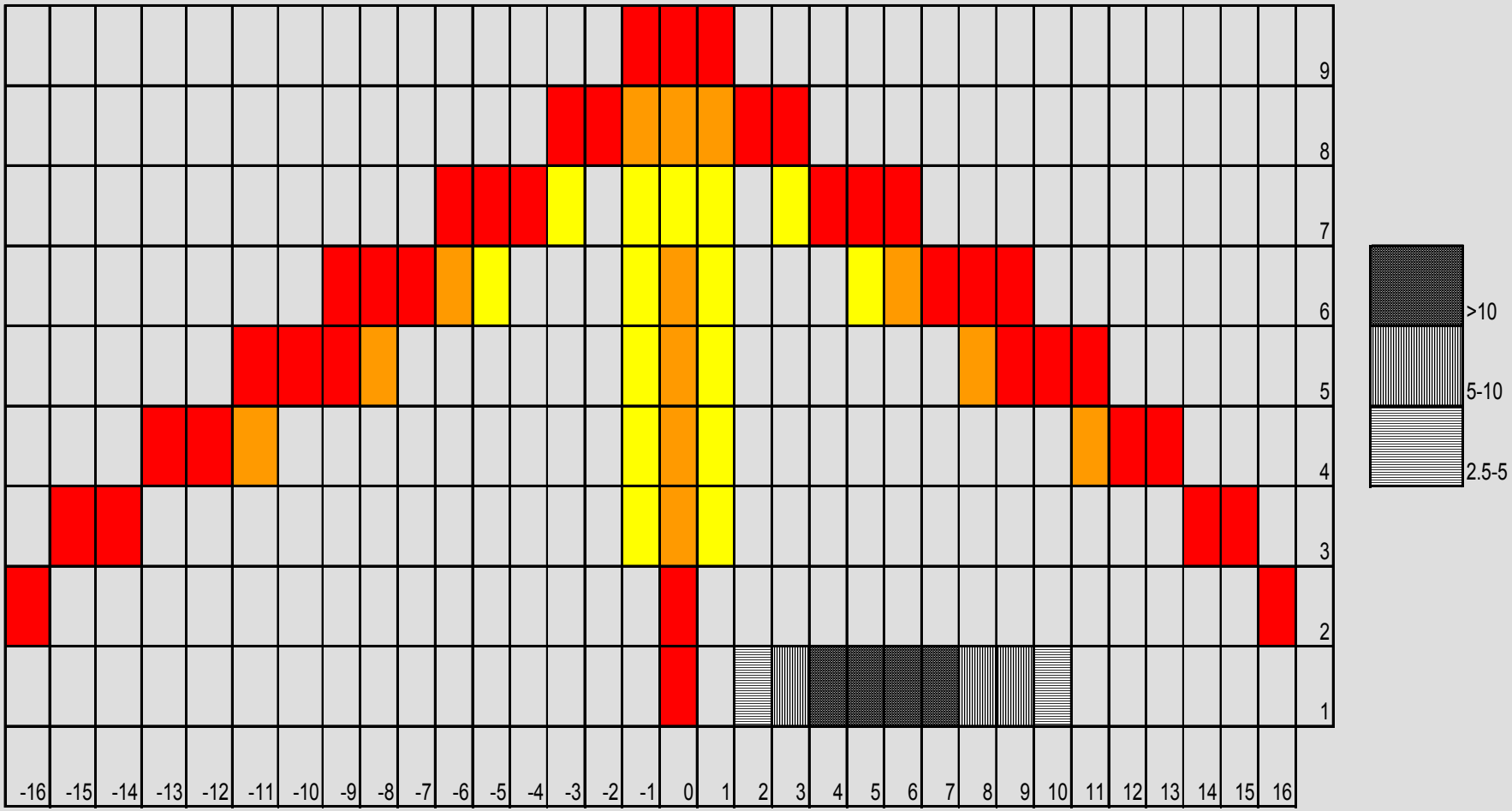
Exclusion Zones for 50 Micron Core Fiber



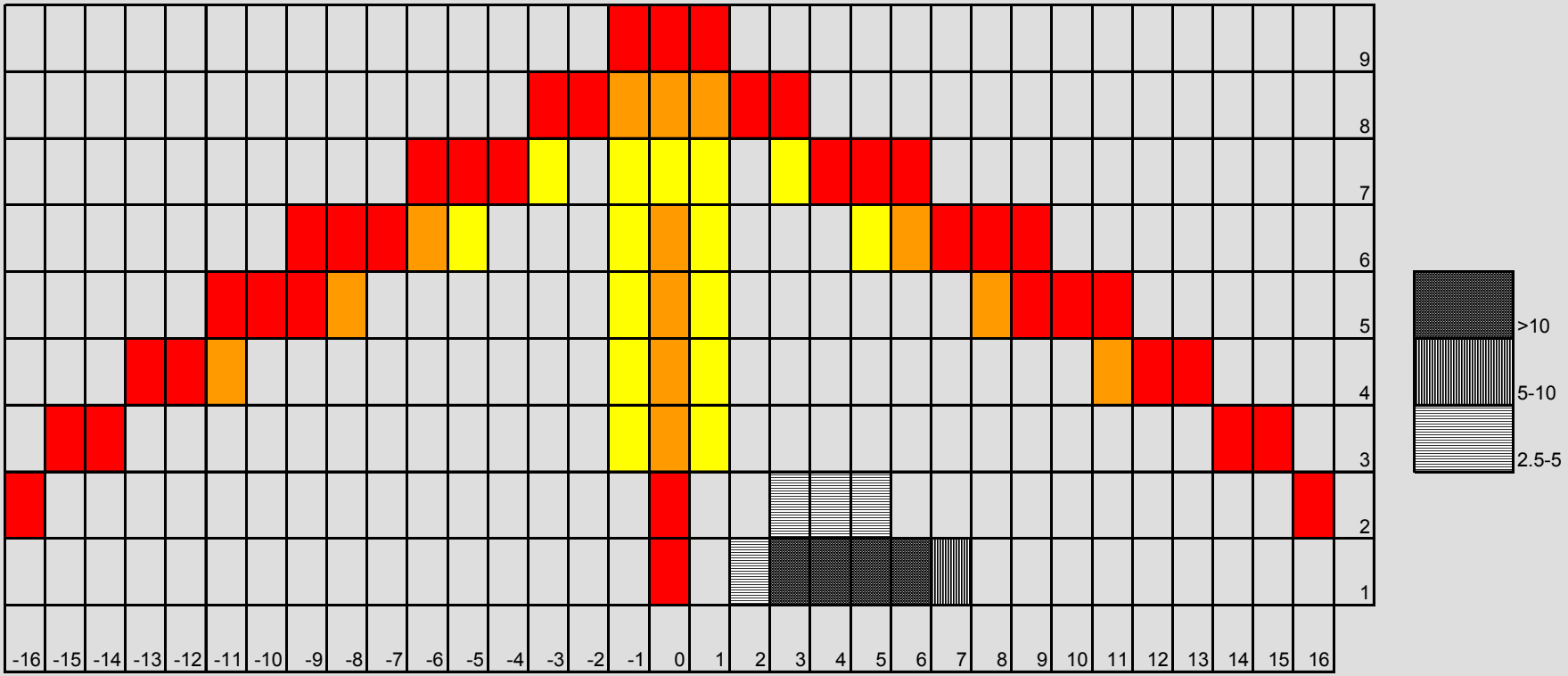
Mode Excitation for 20 Micron Offset Launch
4.5x4.5 Micron Beam: 62.5 Micron Fiber

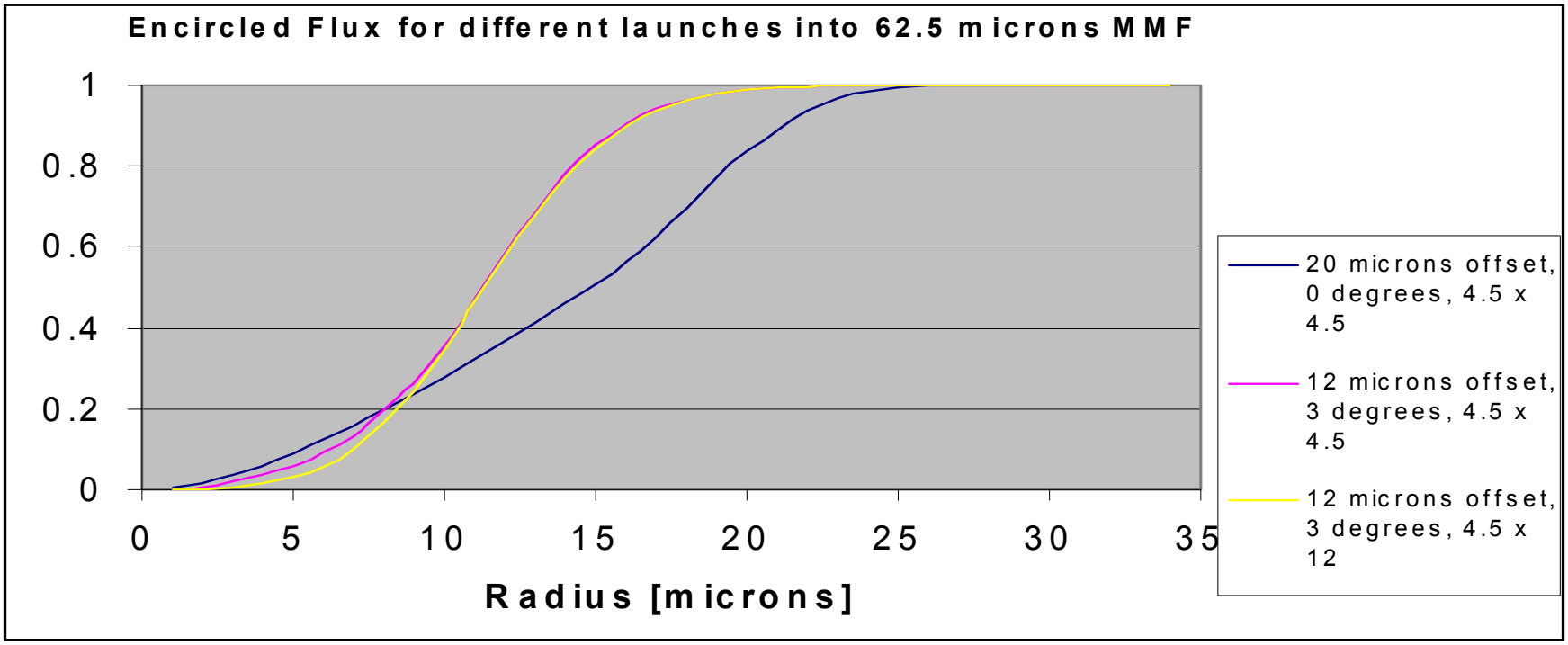


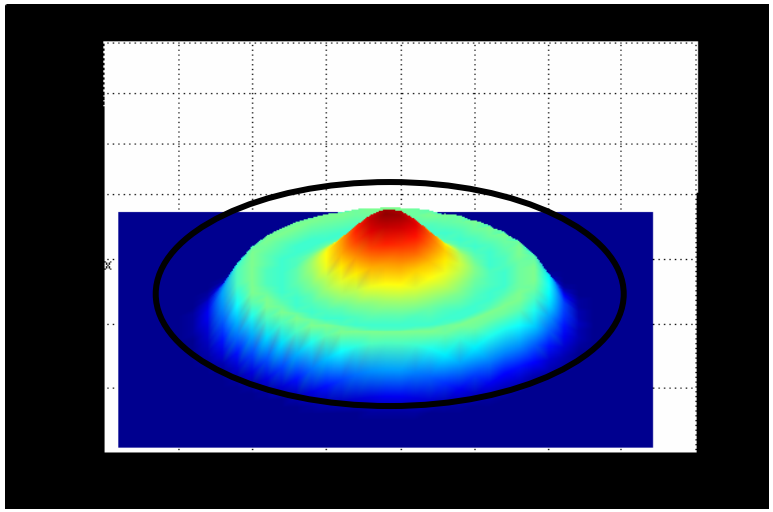
Mode Excitation for Spiral Launch 4 Degree Angle, 12 Micron Offset, 4.5 x 4.5 Micron Beam



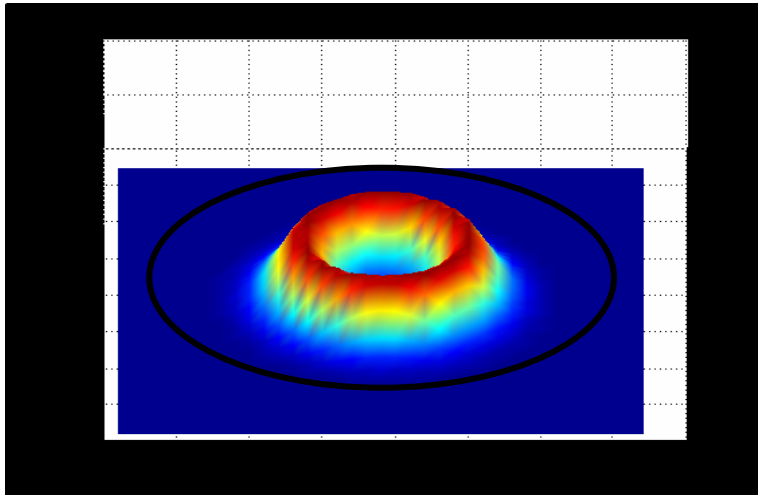
Spiral Launch 3 Degree Angle, 12 Micron Offset 4.5 x 12 Micron Beam







Offset Launch



Spiral Launch

II. Bandwidth Simulations for Offset Launch and Spiral Launch

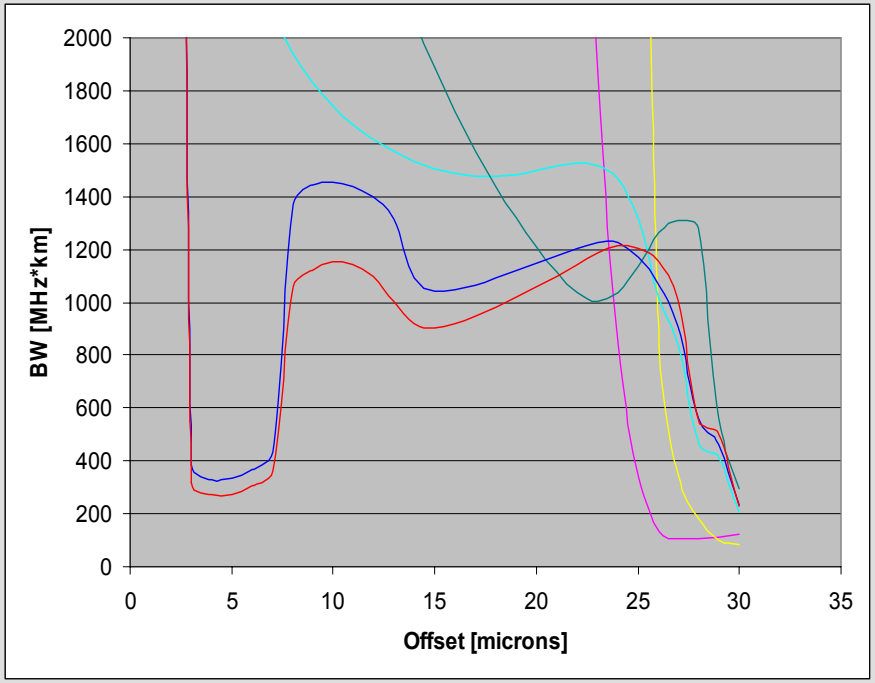
Initial Simulation Methodology

- **Simulation were done using a subset of the modes of an infinite quadratic index profile fiber**
  - All modes with $n_{eff} < n_{cladding}$ were discarded
  - Modes of infinite quadratic fiber are very similar to truncated clad fiber except for those modes very close to cut-off
- **Index defects are analyzed as perturbations of baseline fiber**
- **Mode power distribution calculated for each launch method**
- **Group velocities calculated for each mode in the presence of the index defects**
- **Fiber impulse response and bandwidth calculate based on population of modes launched and the modal delays**
- **No mode dependent loss included**

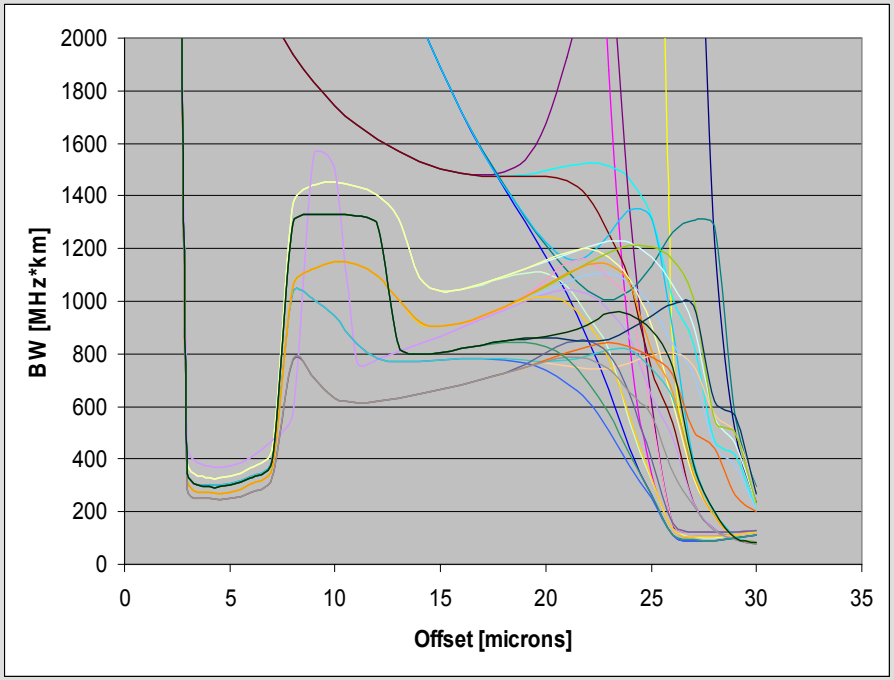
Fiber Index Defects

- Central peak or dip: Index defect assumed to have Gaussian shape with FWHM of 3 microns
- Outer Peak or Dip: Index dip is abrupt drop to cladding index at lower than normal radius, peak is 3 micron FWHM increase
- Profile error: Deviation from optimum power law index variation
- Defect amplitudes set so that when only one defect is present, the OFL bandwidth is 500 MHz-km
- 27 fiber combinations evaluated
- Most fibers with multiple defects have OFL bandwidths less than 500 MHz, but no scaling adjustments were made

Conventional Offset Launch: 62.5 Micron Fiber

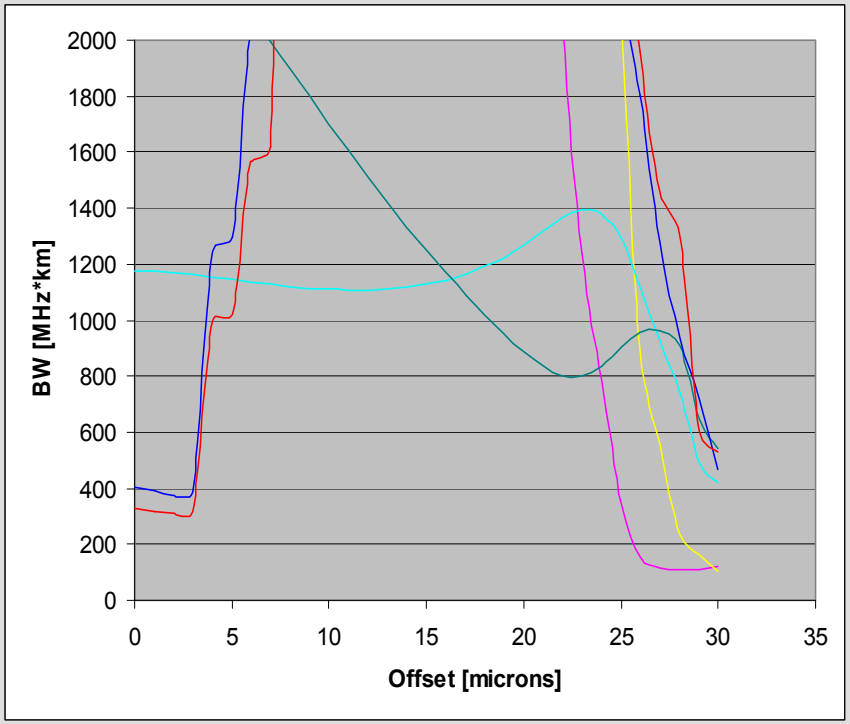


Fibers with only single defect

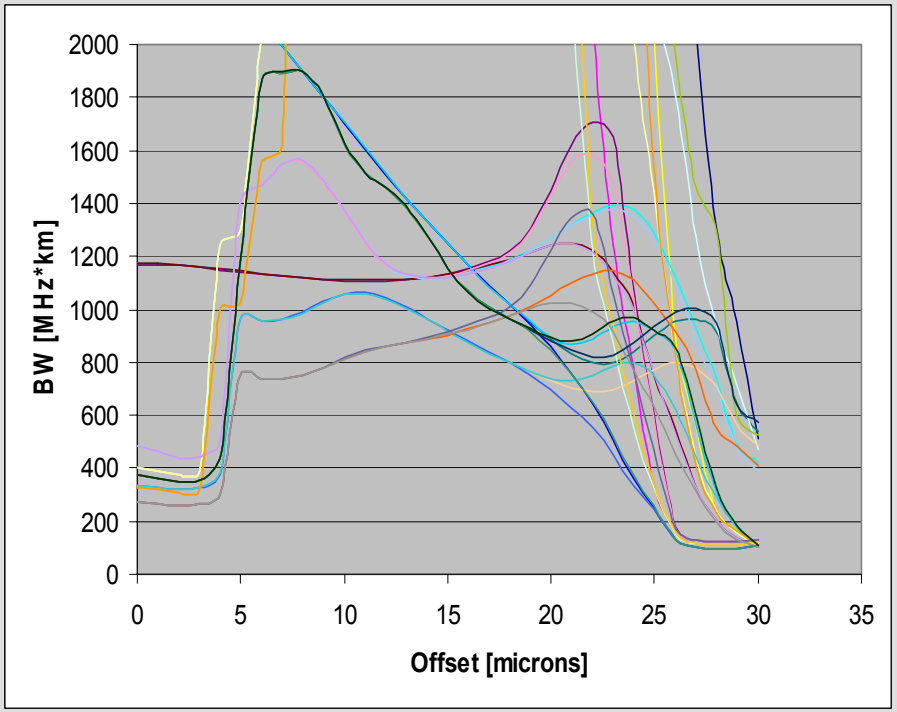


All fibers

Spiral Offset Launch: 4.5x4.5 Micron Beam, 3 Degree Angle, 62.5 Micron Fiber

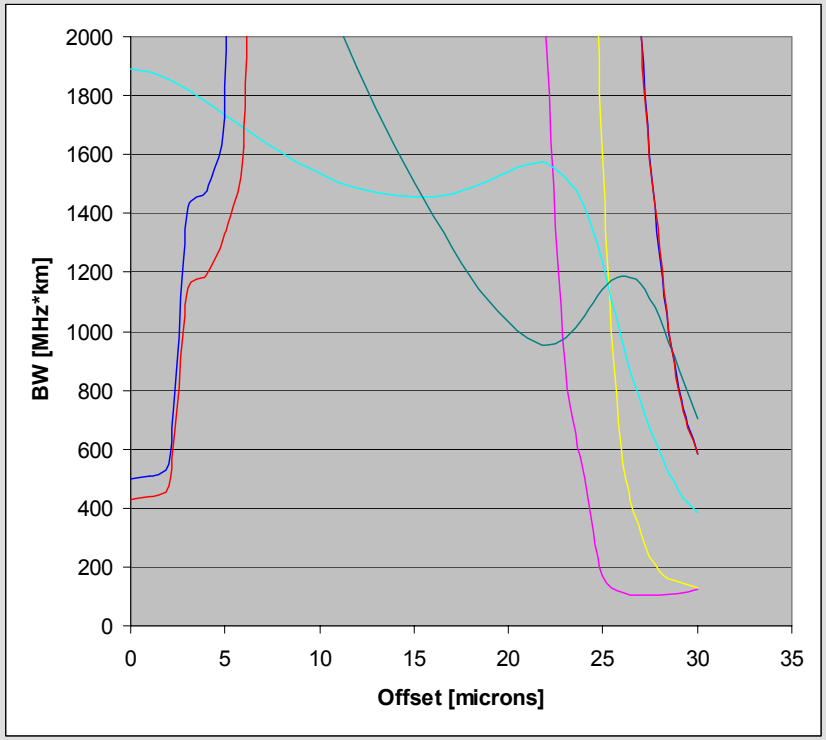


Fibers with only single defect

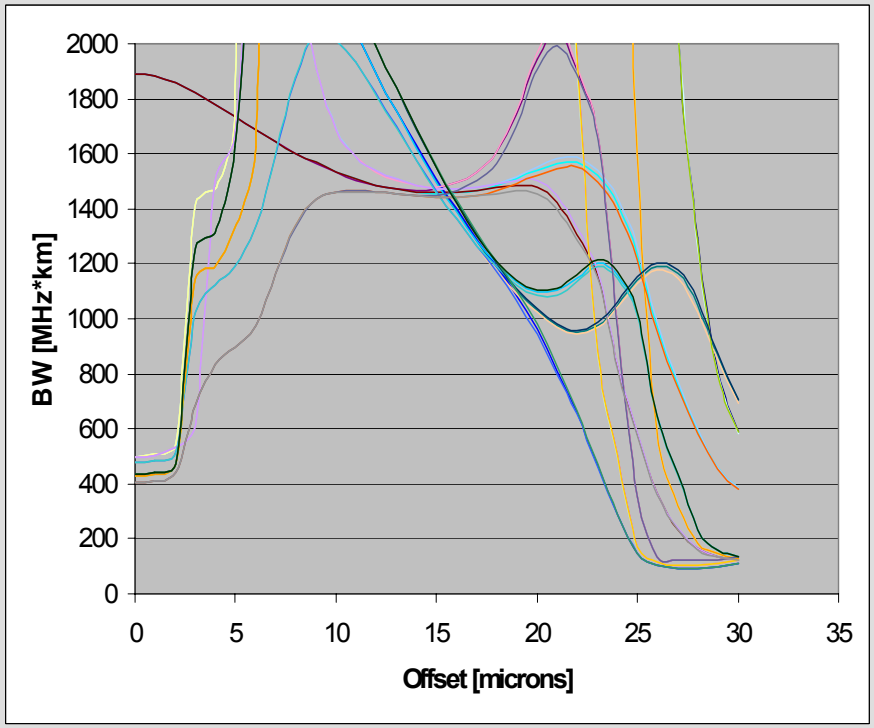


All fibers

Spiral Offset Launch: 4.5x12 Micron Beam, 3 Degree Angle, 62.5 Micron Fiber

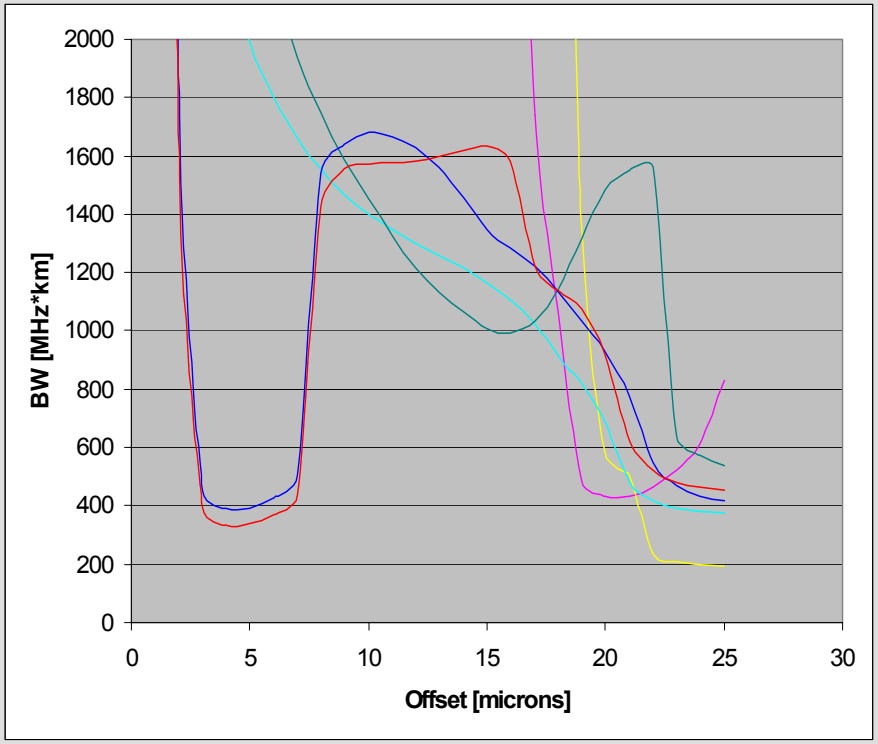


Fibers with only single defect

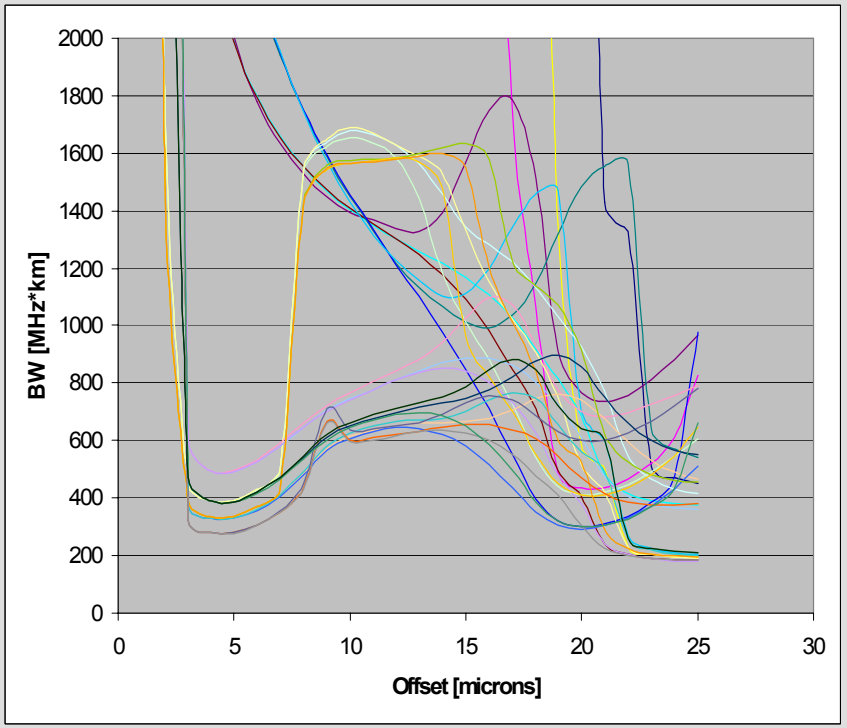


All fibers

Conventional Offset Launch: 50 Micron Fiber

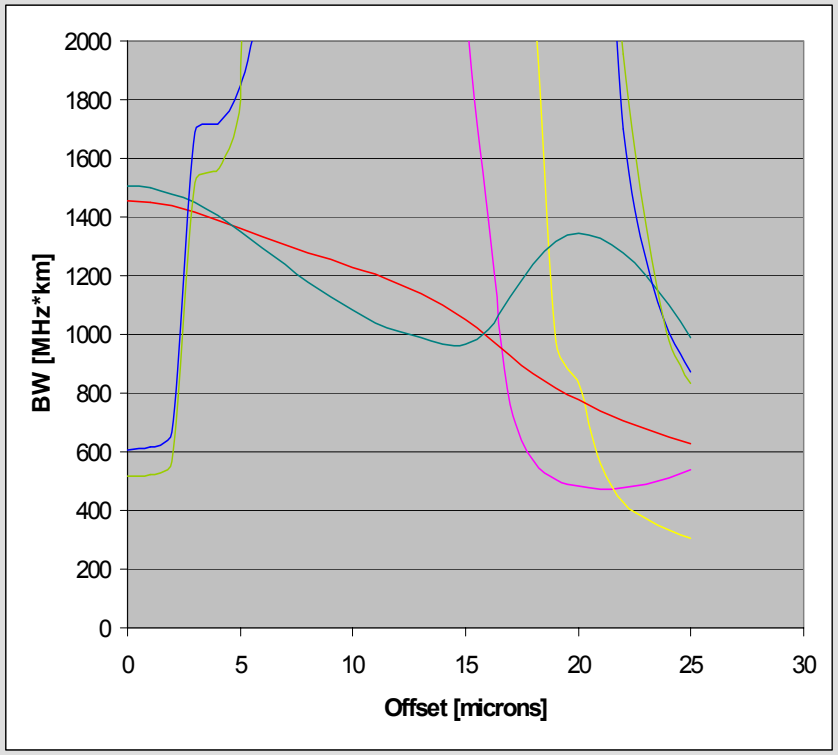


Fibers with only single defect

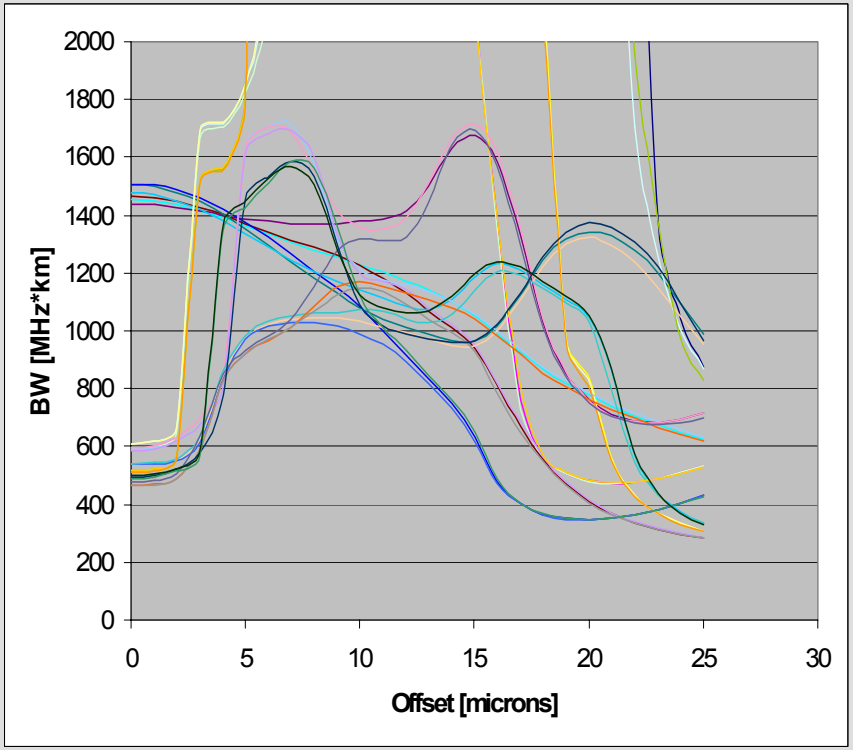


All fibers

Spiral Offset Launch: 4.5x12 Micron Beam, 3 Degree Angle, 50 Micron Fiber



Fibers with only single defect



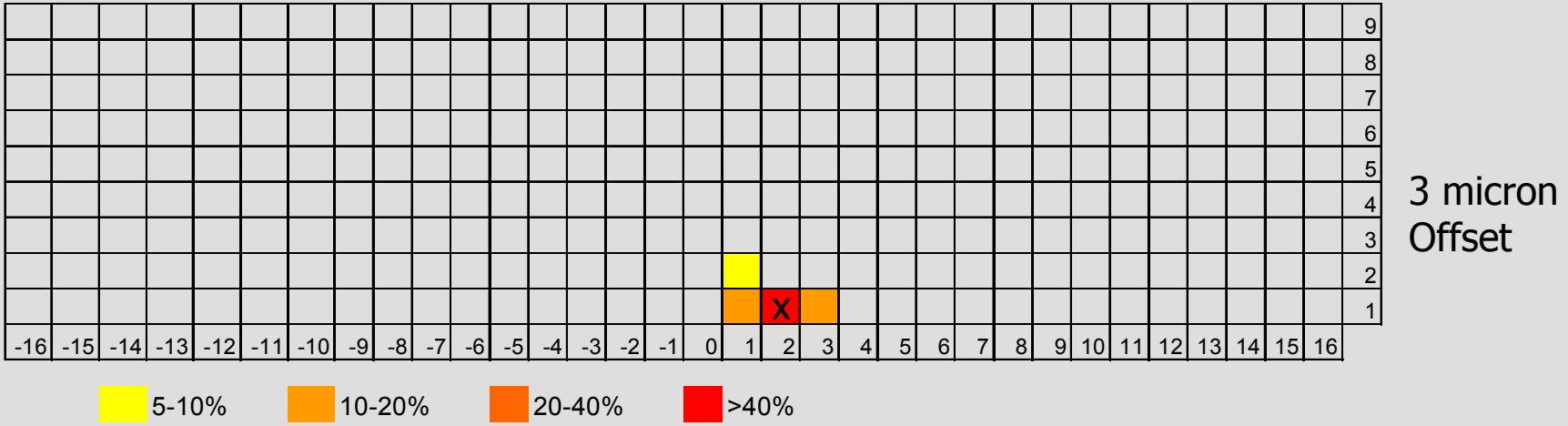
All fibers

III. Simulations of the Effects of Misalignments at Connectors

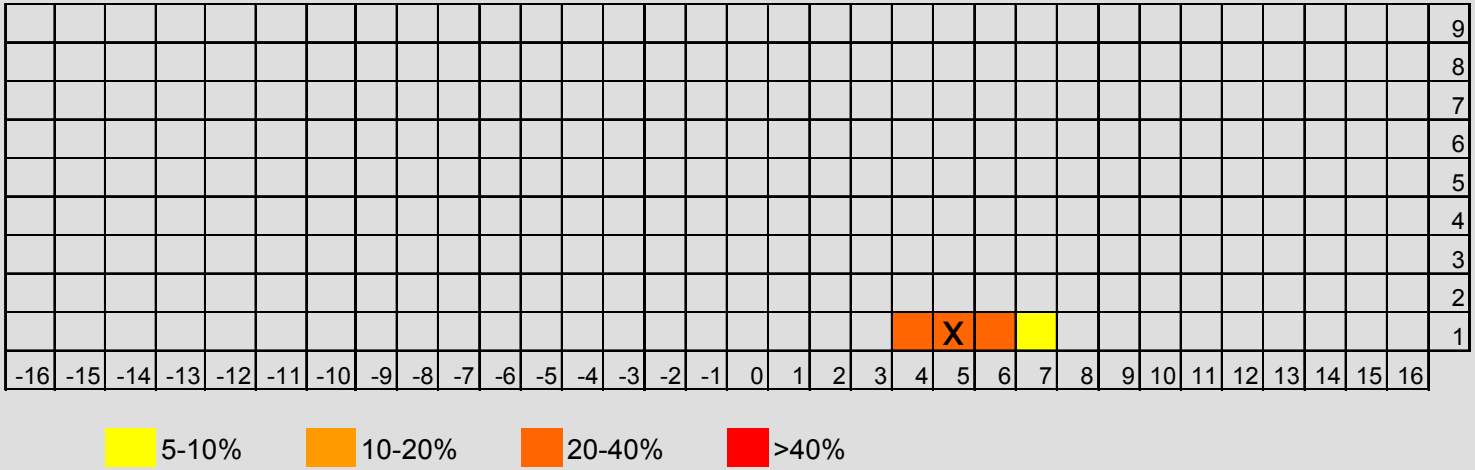
Effect of Connector Misalignments on Modal Power Distribution

- Fiber bandwidth determined by the modal power distribution through main length of transmission fiber
- Modes couple at misaligned connectors and due to fiber micro and macro bends
- Net effect is a diffusion of the modal population from that of the initial launch
- Width of distribution of principle mode numbers will tend to increase, decreasing bandwidth from profile error defects for both offset and spiral launch

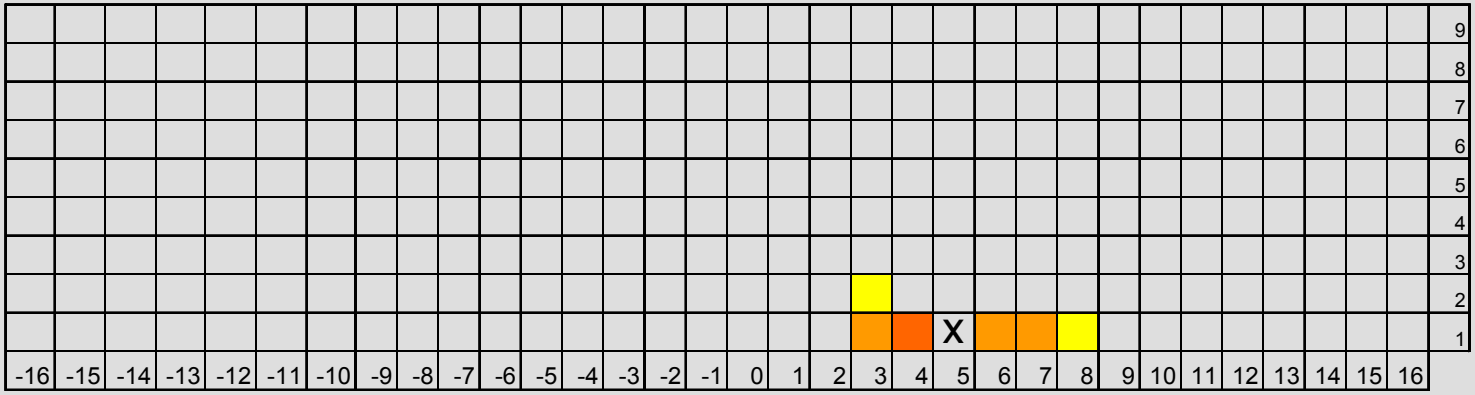
Diffusion of Power from L=2 M=1 Mode at Offset Connector



Diffusion of Power from L=5 M=1 Mode at Offset Connector

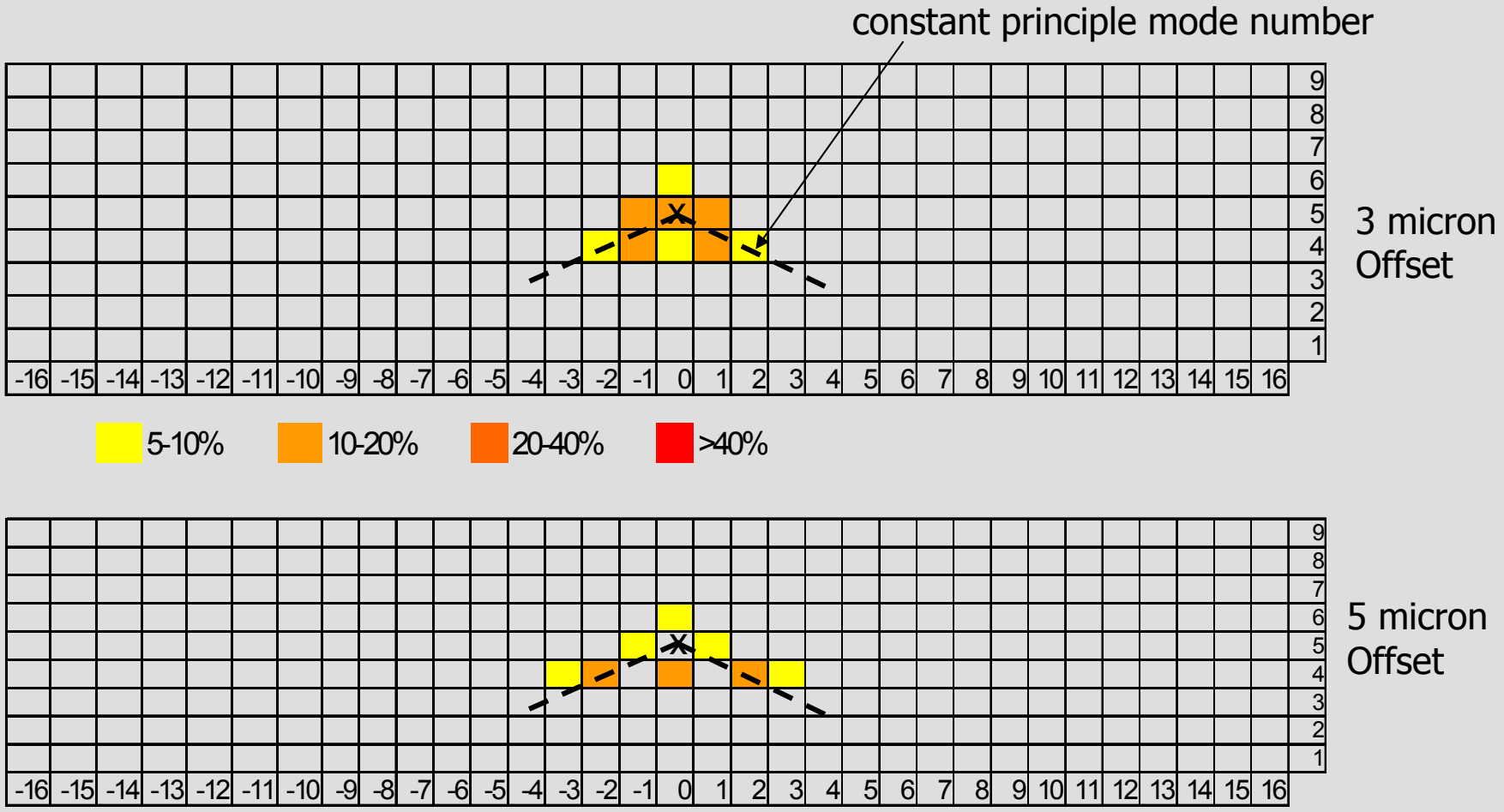


3 micron Offset

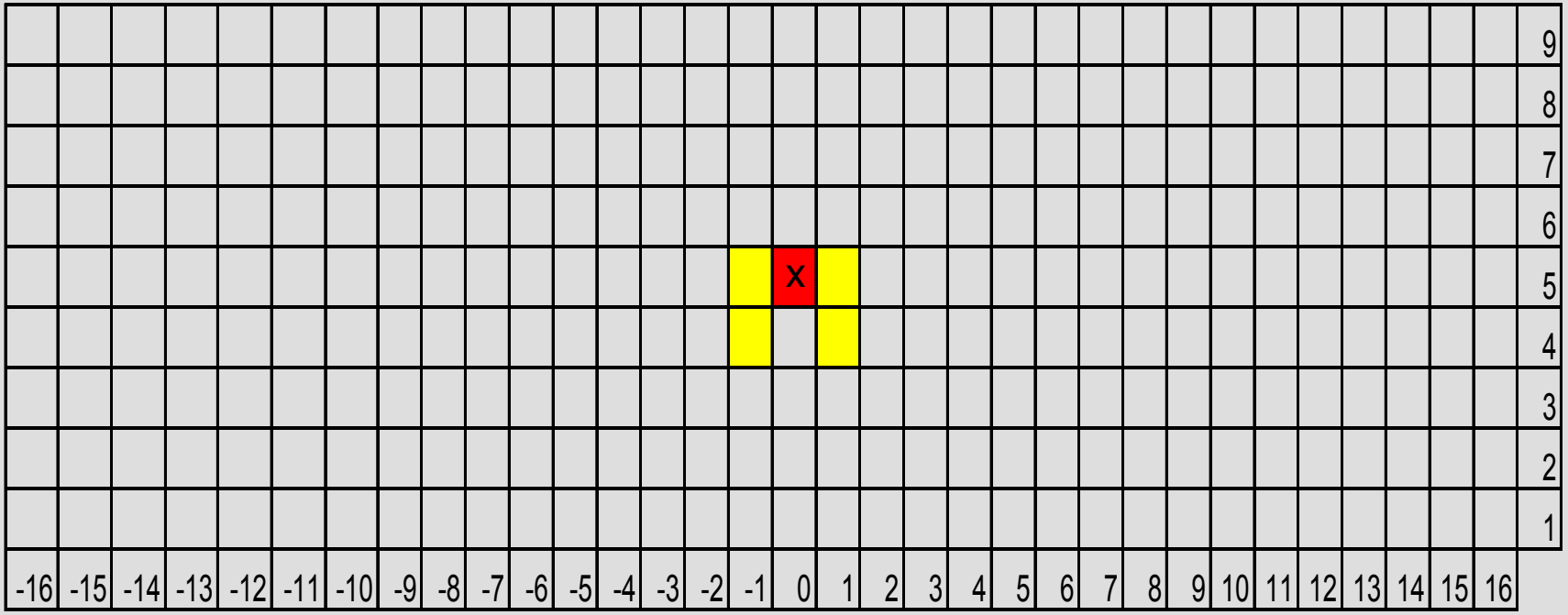


5 micron Offset

Diffusion of Power from L=0 M=5 Mode at Offset Connector



Diffusion of Power from L=0, M=5 Mode at 1 μm Offset Connector



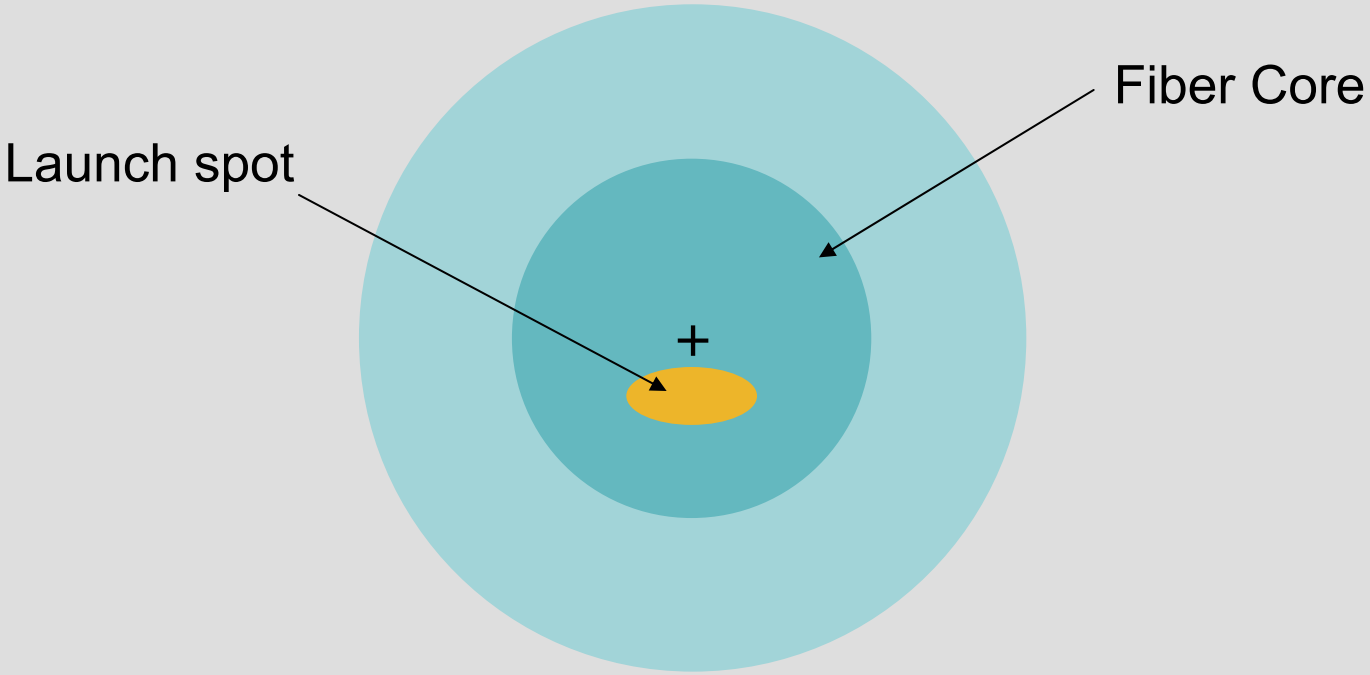
Power couples to L,M orders +/- 1 from original

Summary of Mode Coupling Characteristics

- Mean azimuthal mode number, L, is unchanged after mode coupling at offset connector
- Standard deviation of distribution of L and M values after connector proportional to the connector offset and proportional to the square root of the initial principle mode number
- For weak coupling, power couples primarily to modes with +/-1 change in L and/or M number
- Diffusion of modal power distribution is biased towards modes with similar principle mode index
- Diffusion of modal power moves spiral launch distribution closer to exclusion zones, but low L, M order modes with power near central defect diffuse less
- Bandwidth advantage of spiral launch is expected to decrease, but still remain significant, in the presence of multiple misaligned connectors and other mode coupling mechanisms

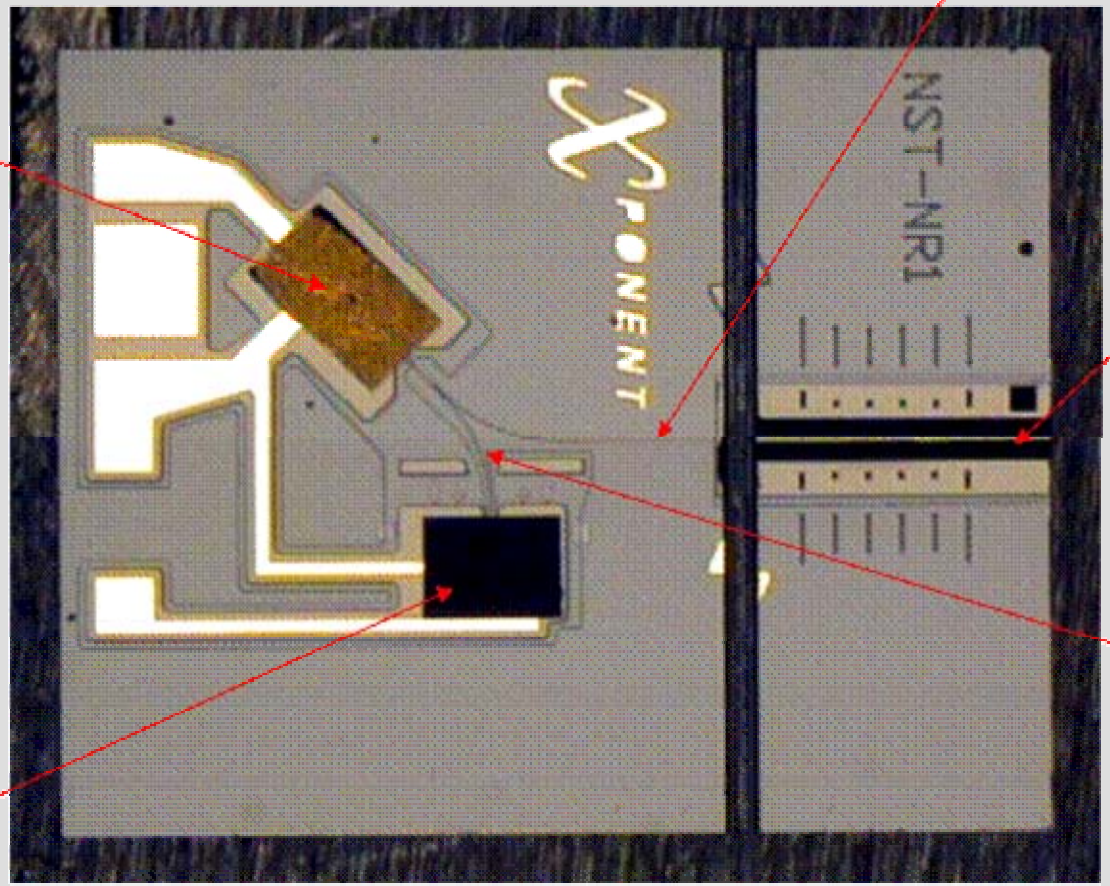
IV. Selected Implementation Methods for Spiral Launch

Spiral Launch Implementations: Elliptical Beam

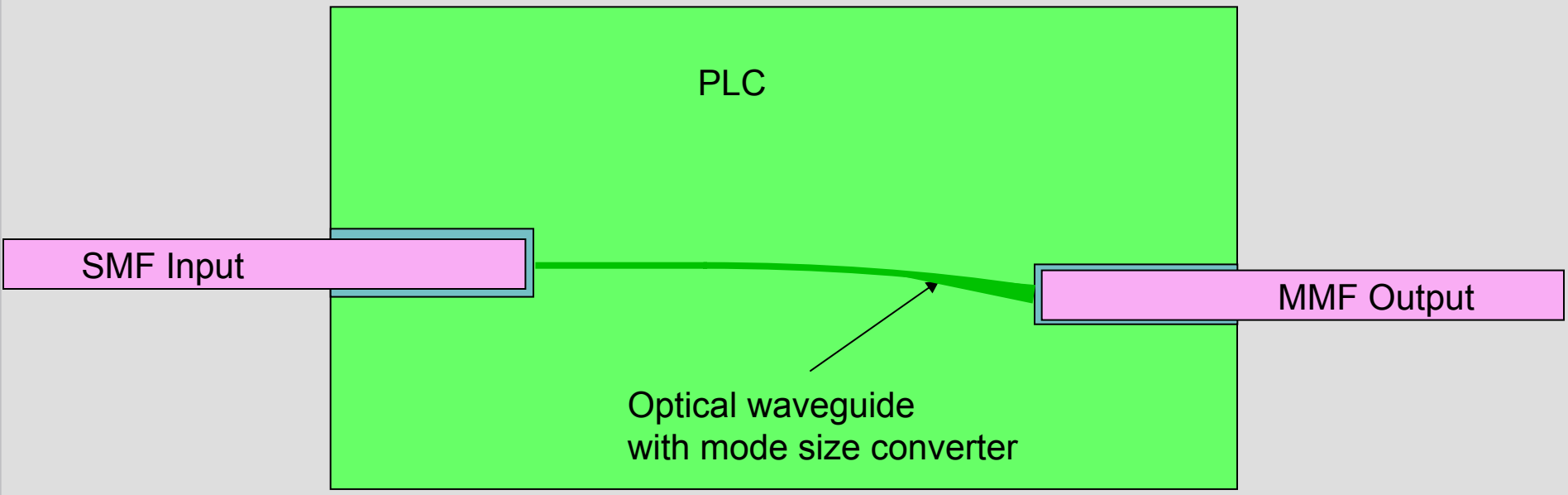


Vertical offset implemented by V-groove width
Azimuthal angle implement by PLC waveguide angling
Elliptical beam implemented by PLC waveguide spot size converter

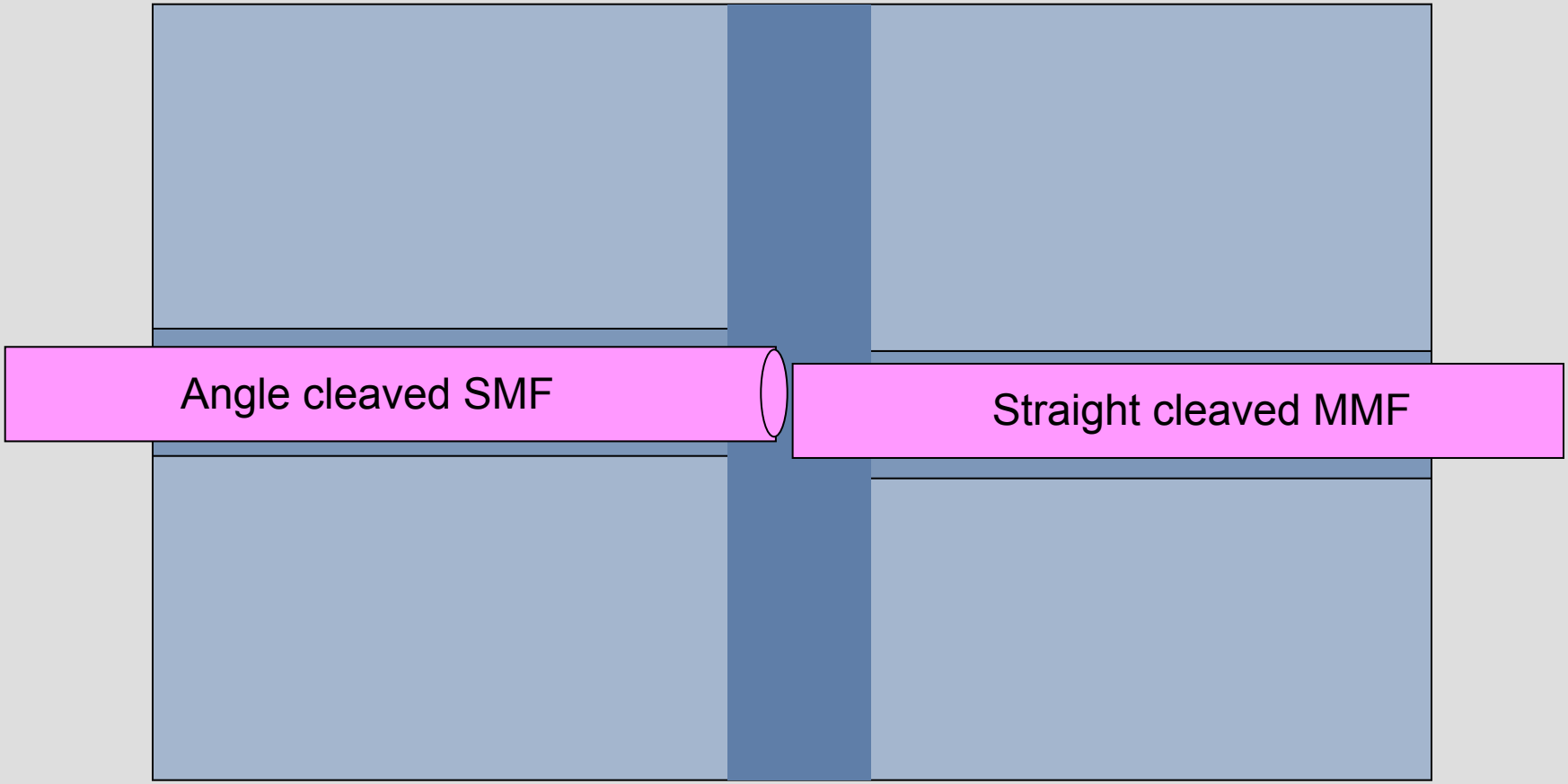
PLC Implementation Compatible with Spiral Launch



Stand Alone PLC Spiral Launch Mode Conditioner: Elliptical Beam Launch



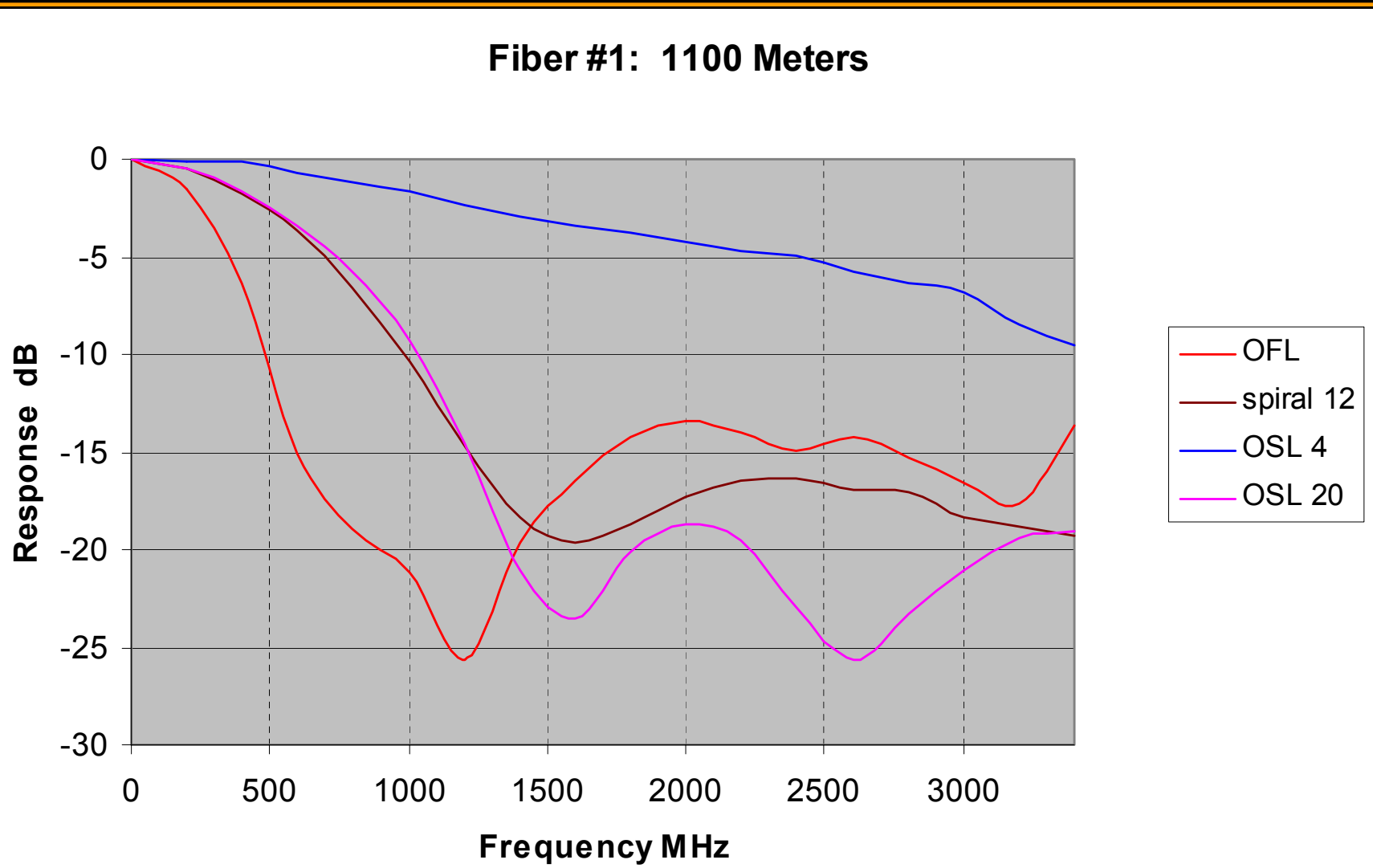
Spiral Launch Silicon Optical Bench Implementation: Circular Beam only



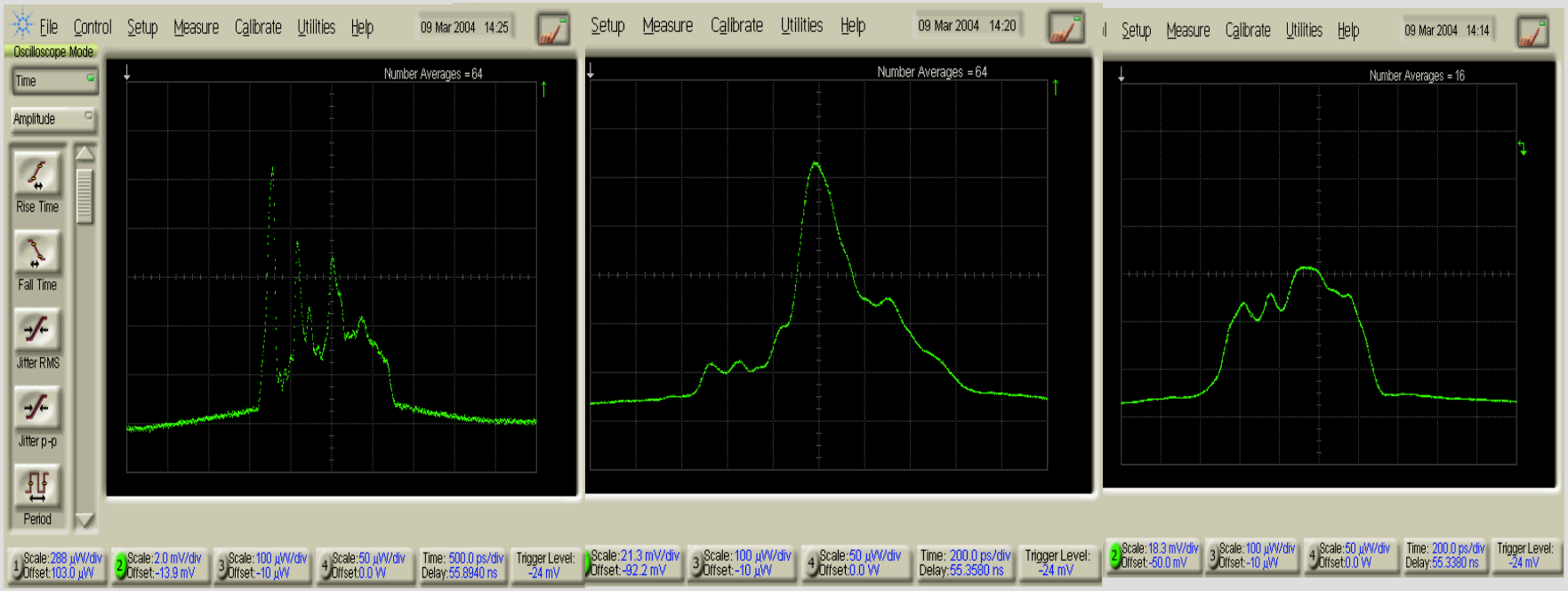
V. Initial Test Results for Spiral Launch

Initial Test Result Overview and Limitations

- **A primary objective of the spiral launch is to suppress DMD related to central index defects**
- **None of the fibers used for initial tests have a significant central index defect**
- **Results for spiral launch are representative of what is expected in the presence of a central defect**
- **Initial results are for spiral launch with a circular beam. Spiral launch with an elliptical beam is predicted to be substantially better**
- **Bandwidth and impulse response were measured for three 62.5 micron core fiber reels (two 1.1 km and one 550 m)**
- **Tests done for four launch conditions**
  - Overfilled with step index type mode scrambler
  - 4 μm offset launch: Strong indicator of presence of central defect
  - 20 μm offset launch
  - 12 μm, 3.5 degree spiral launch with circular beam
- **Conditioned launch versions implemented with silicon optical bench designs**


Fiber #1: 1100 Meters
Response dB
0
-5
-10
-15
-20
-25
-30
0
500
1000
1500
2000
2500
3000
Frequency MHz
OFL
spiral 12
OSL 4
OSL 20

Impulse Response Fiber 1

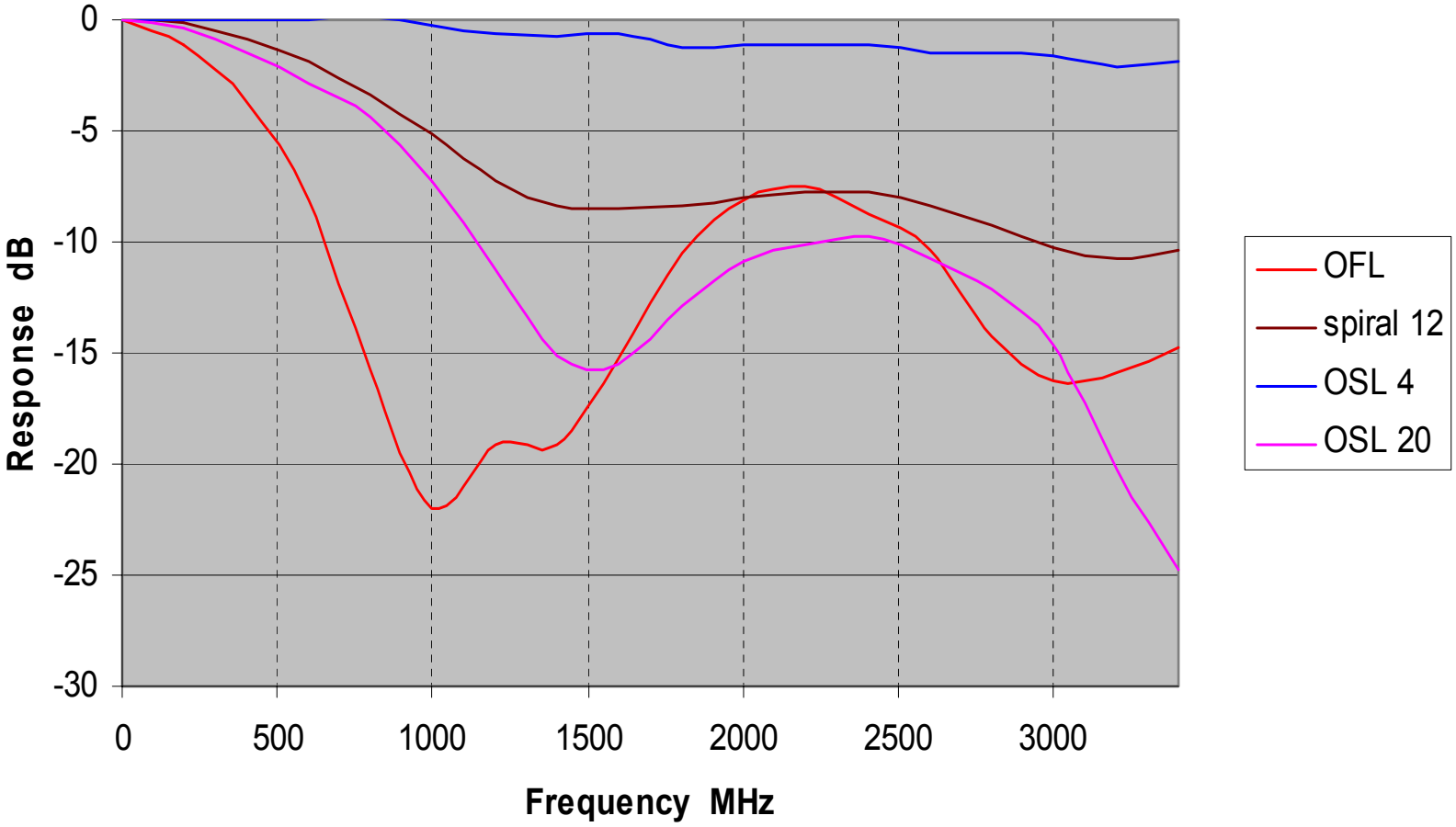


OFL 500 ps/div

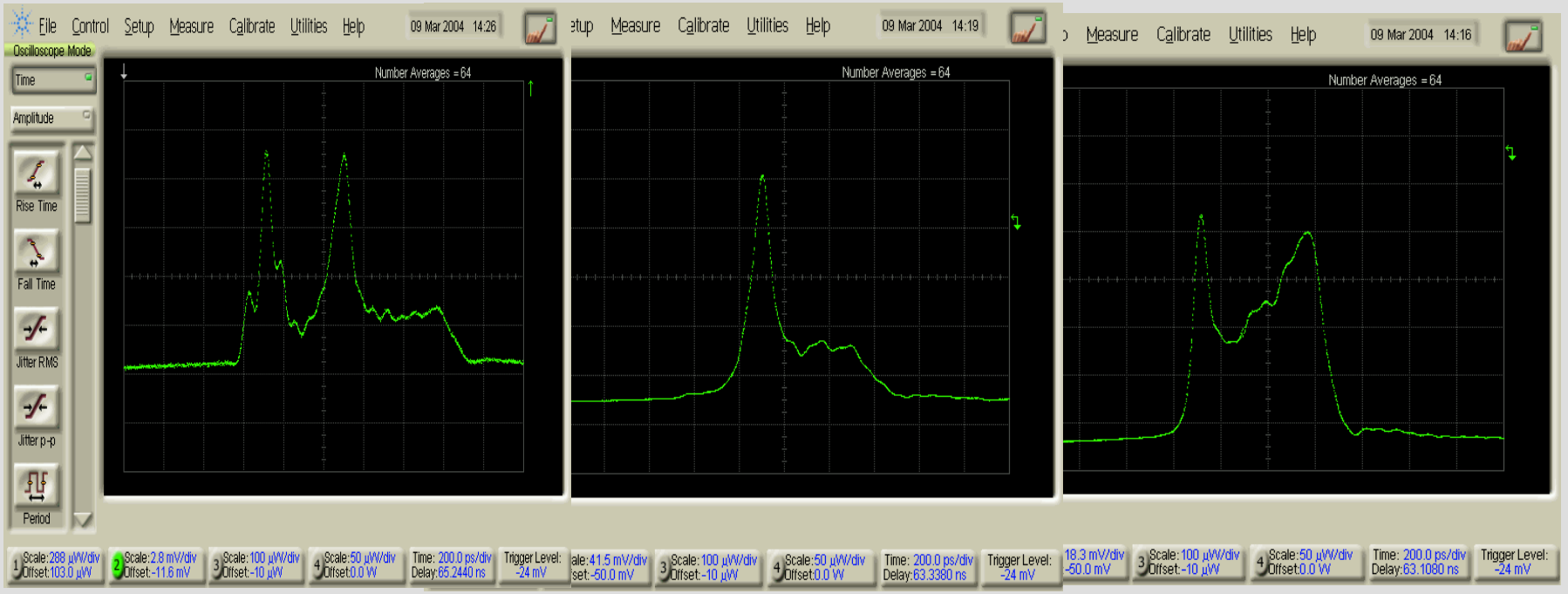
Spiral launch 200 ps/div

OSL 200 ps/div

Fiber #2: 1100 Meters



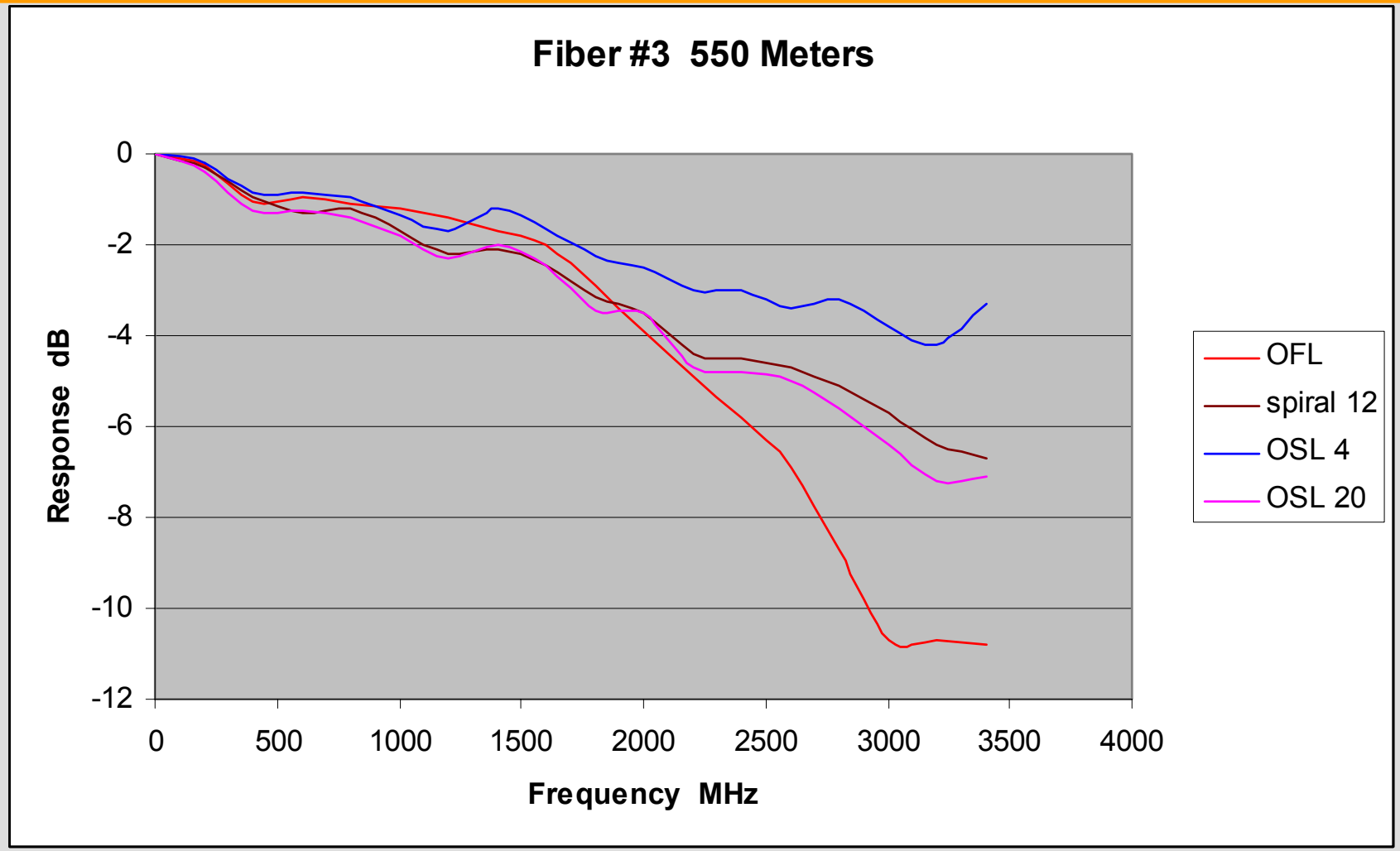
Impulse Response Fiber 2



OFL 200 ps/div

Spiral launch 200 ps/div

OSL 200 ps/div


Fiber #3 550 Meters
Response dB
0
-2
-4
-6
-8
-10
-12
0
500
1000
1500
2000
2500
3000
3500
4000
Frequency MHz
OFL
spiral 12
OSL 4
OSL 20

Test Result Summary

- Key test of suppression of DMD related to central index defects by spiral launch not possible because test fibers lacked central index defects
- Both offset launch and spiral launch substantially outperformed overfilled launch
- Spiral launch bandwidth comparable to slightly better than offset launch for these test fibers
- Significant improvements for spiral launch compared to offset launch expected for fibers with central index defects and for spiral launch with elliptical beam shape

Planned Next Steps

Continue simulation work

- Analysis using exact modes of fibers with defects
- Expand range of defect fibers in simulation
- Modeling of link bandwidth including mode coupling and mode dependent loss
- Modeling of potential spiral launch compliance test methods

Experimental work

- Link bandwidth measurements on “worst case” fibers with central index defect
- Build TOSA with elliptical spiral launch
- Encircled flux measurements, before and after fiber transmission
- Coupled power ratio (CPR) measurements

Summary

- Spiral launch method has the potential for significantly mitigating adverse effects of index profile defects
- Spiral launch predominantly excites modes that have negligible overlap to central and outer index defects
- Simulation results indicate an enhancement of bandwidth by 1.6x for 50 micron fiber and >2x for 62.5 micron fiber compared to conventional offset launch
- A single spiral launch condition appears possible for use with both 50 and 62.5 micron fibers while maintaining bandwidth greater than that of separately optimized offset launches; would enable integrated TOSA launch
- Spiral launch can be implemented at low cost
- Xponent will make available spiral launch components to interested parties for evaluation