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Measurements of VCSEL Mode Delays  
&  
Implications for System Performance

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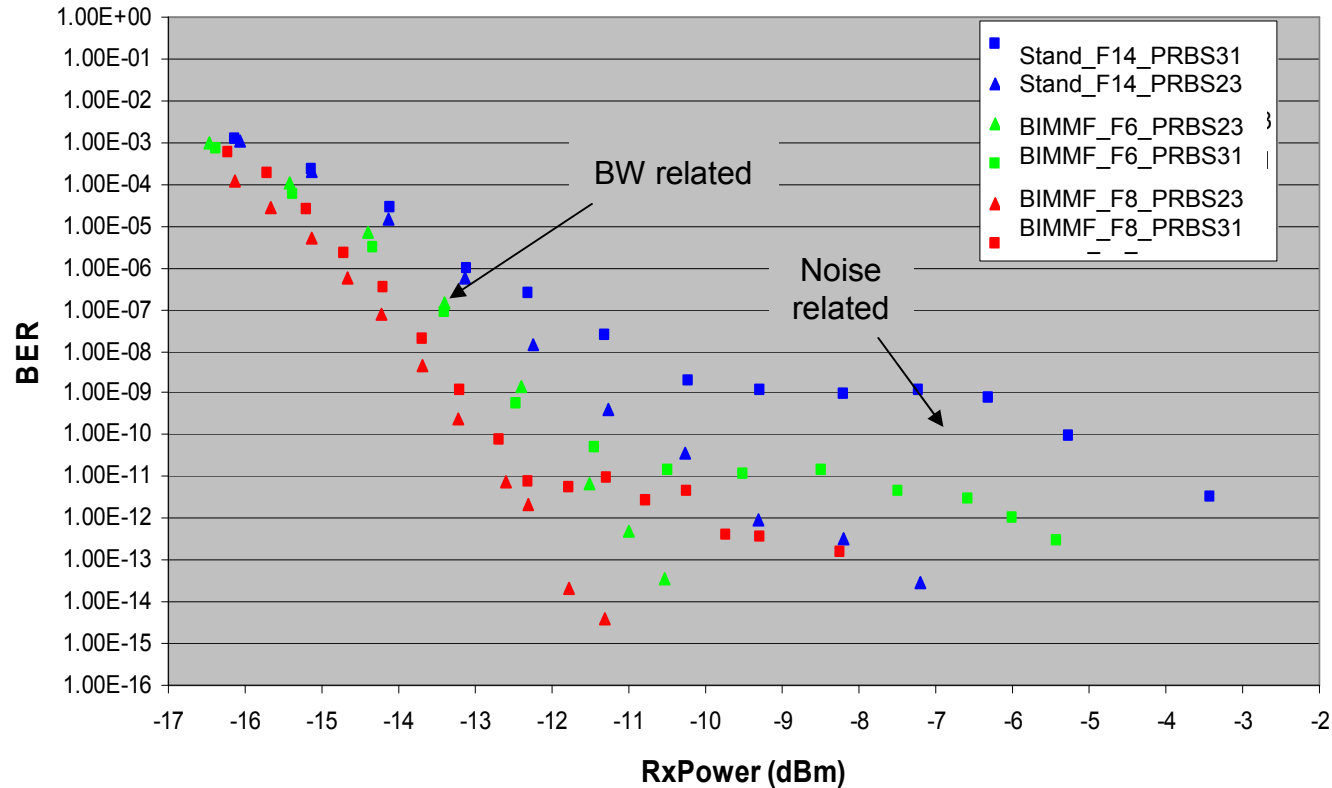
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## Motivation

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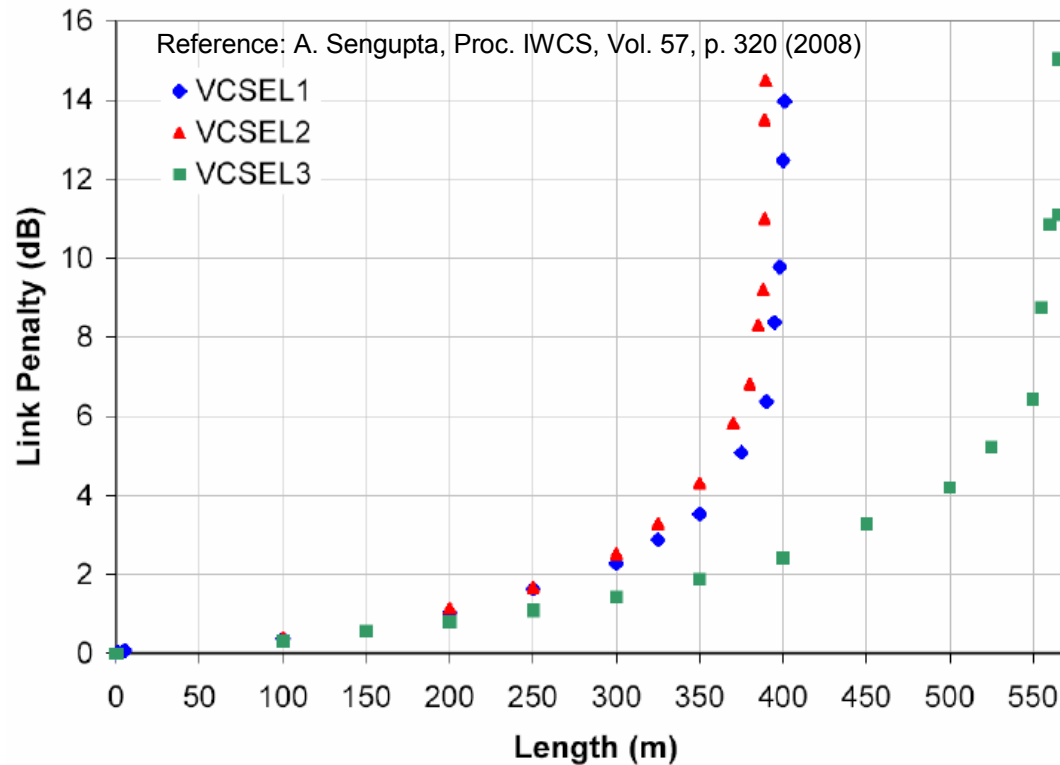
- Pattern Dependent BER shoulders have been observed for transmission over MMF links with Multimode VCSELs
- BER shoulder related penalty divergence is caused by RIN and MPN
- In multimode VCSEL, MPN is related to spatial hole burning
- The question is: does spatial dependence of gain switching cause observable VCSEL modal delays (LMD)
- If LMD is pattern dependent, the deterministic jitter has to be accounted for in the penalty
- Since MPN in VCSEL is related to transverse modes, is there a spatial dependence of spectral width?
- How to account for the spatial dependence of spectral width and LMD in the traditional MPN model?
- Is it possible to design VCSEL with low MPN and characterize MPN performance from spatial measurements?

# Patter Dependent Penalty

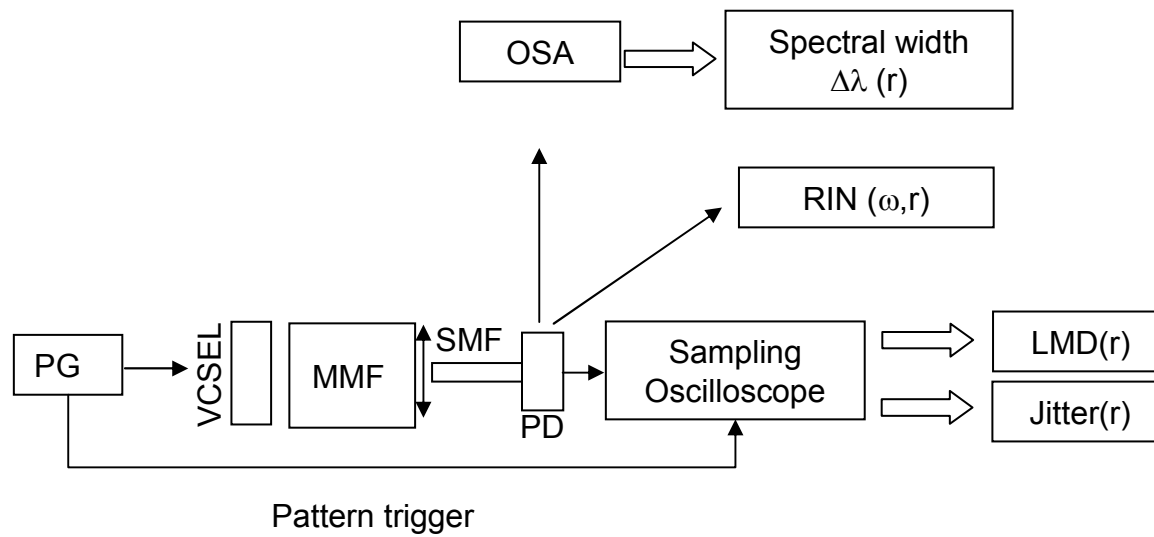


- Both the Standard and BI OM4 fibers show the pattern dependent BER shoulder with 10G PRBS
- What is the source of pattern dependent penalty?
- Whatever the cause is, the errors occur rather infrequently (BER<10E-8)

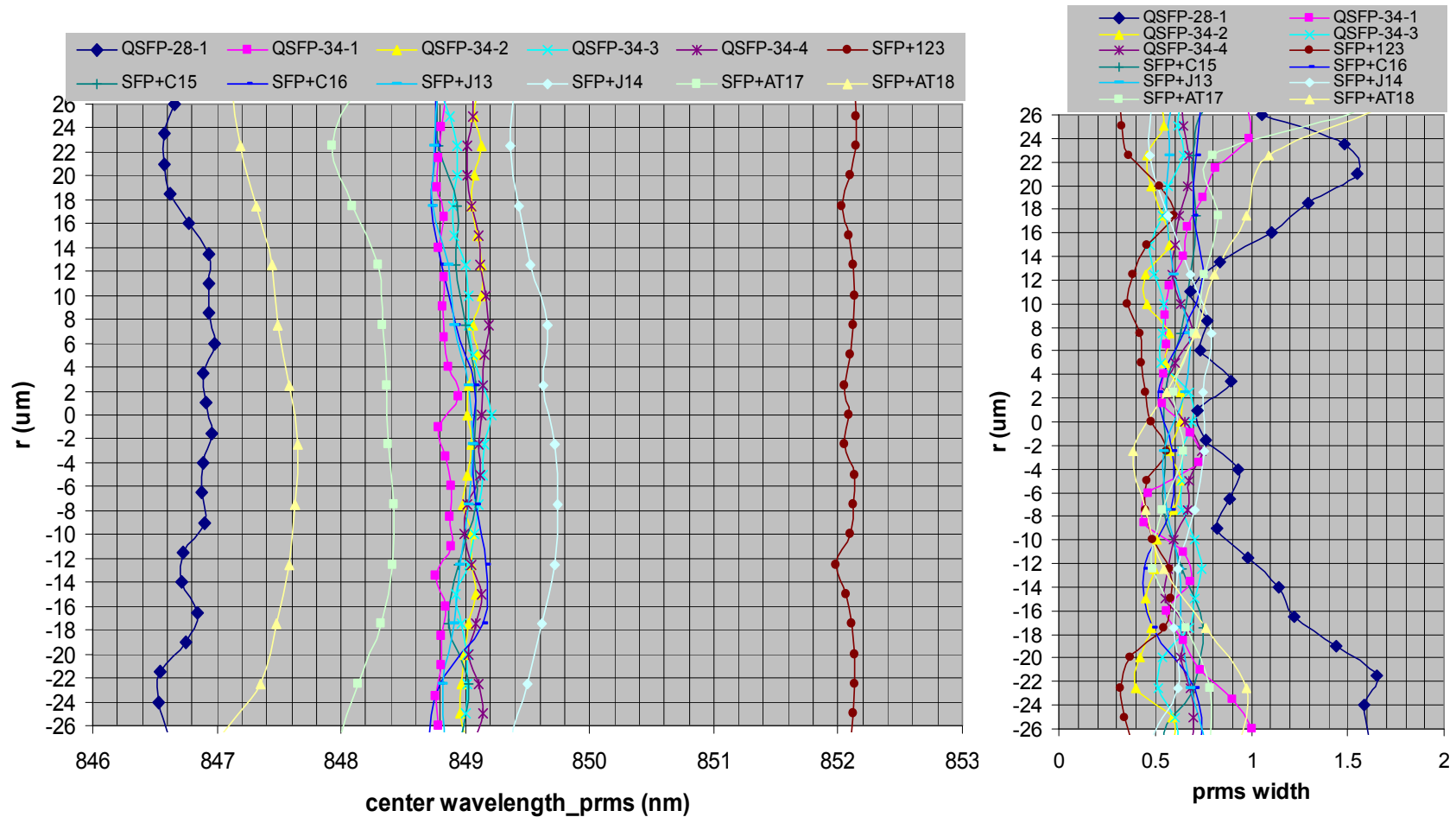
# RIN and MPN related Penalty Divergence



- MMF Link penalty diverges at different characteristic critical lengths for VCSELs with different RIN and MPN
- Simulations show that the point of penalty divergence can be pushed out to longer length by reducing the RIN and MPN



# Radial Dependence of VCSEL Spectra



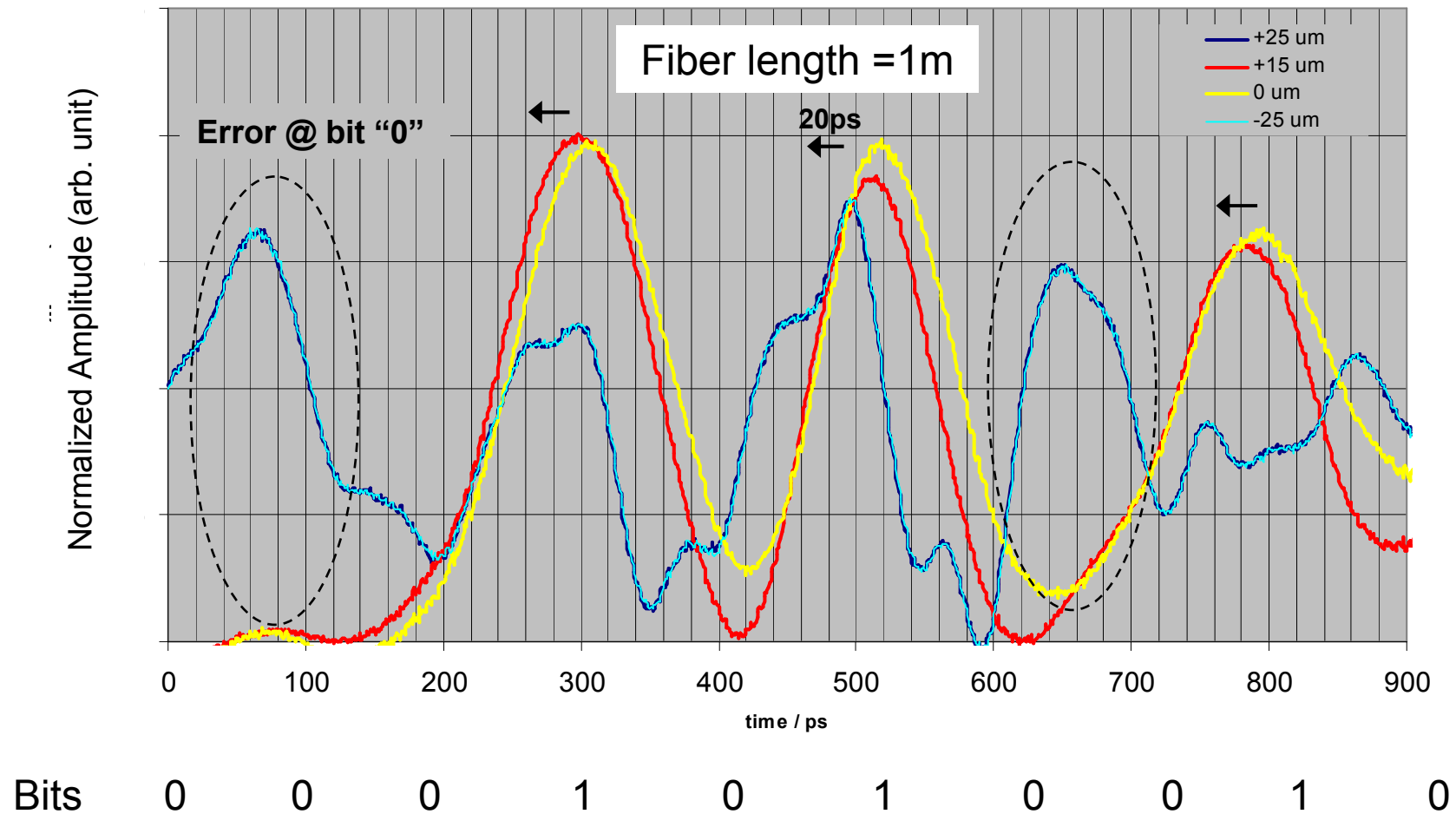
- Clearly, there is an observable radial dependence of the average spectral width
- Spectral width may also vary from one bit to another but the bit level spectral width measurement is difficult

## VCSEL Mode Delay or LMD measurements

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- In absence of chromatic dispersion over a short length of fiber, we should see no temporal changes in the bits even though the spectral width has a radial dependence.
- If the spatial dependence of gain switching cause observable VCSEL modal delays (LMD), can we observe a radial dependence of the LMD?
- Is LMD pattern dependent?

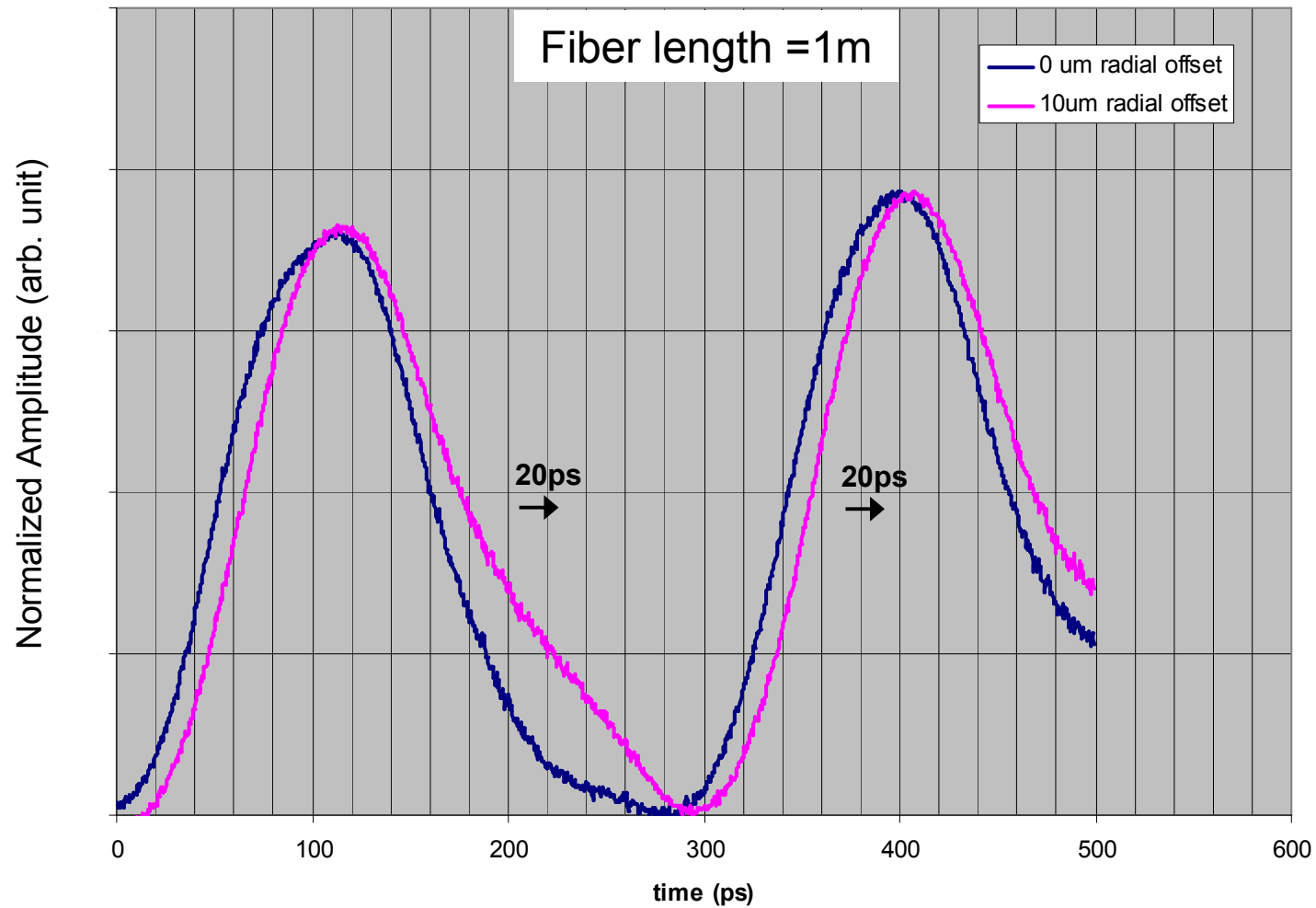
# Pattern Dependent Spatio-Temporal Effect





# MMF-SMF Radial Scan (Short Length)

Higher order modes are delayed relative to low order VCSEL mode



# MMF-MMF Radial Scan (Short Length)

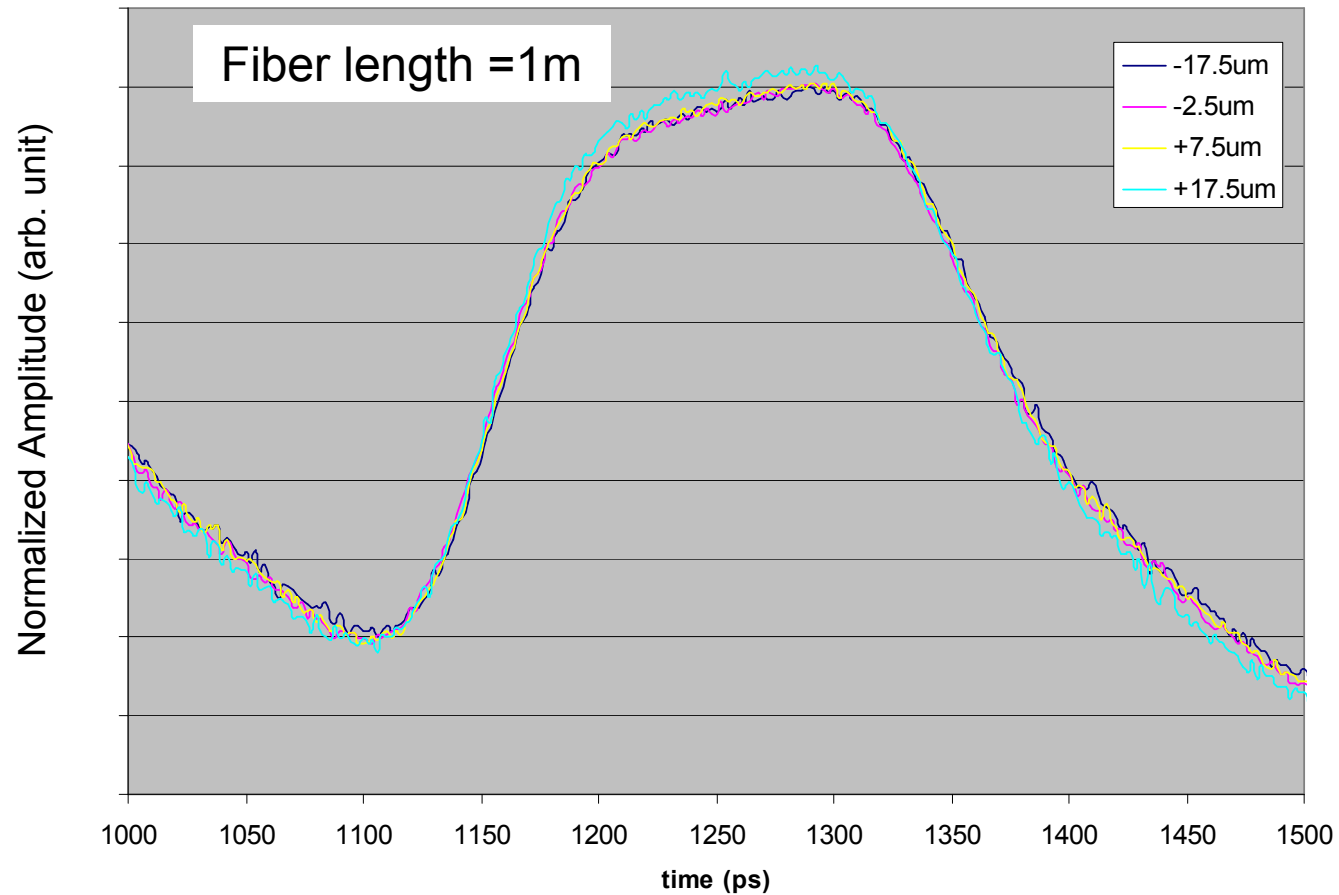
Bits

0

1

1

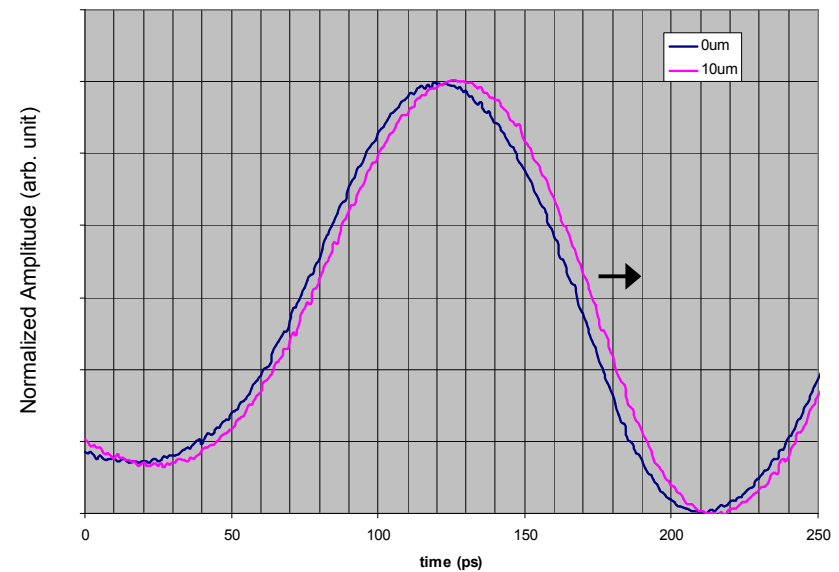
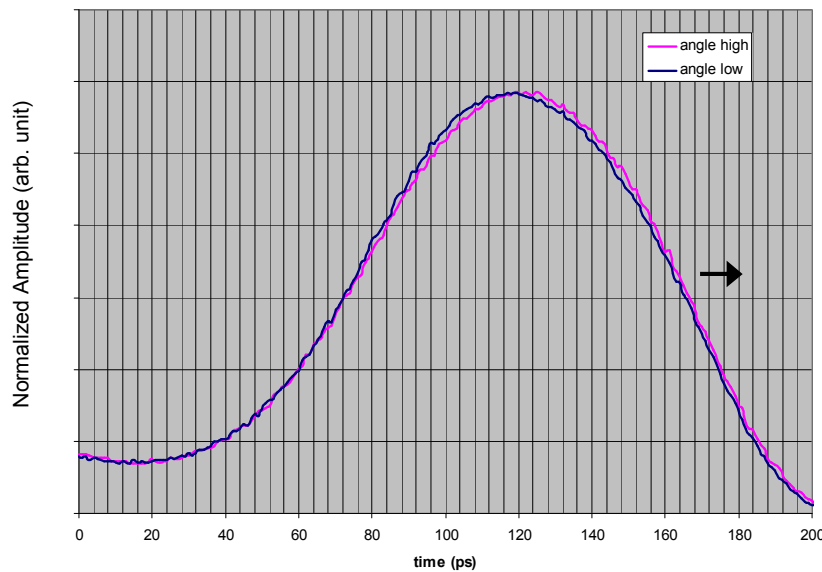
0



No significant changes are noticed due to limited mode filtering by the MMF

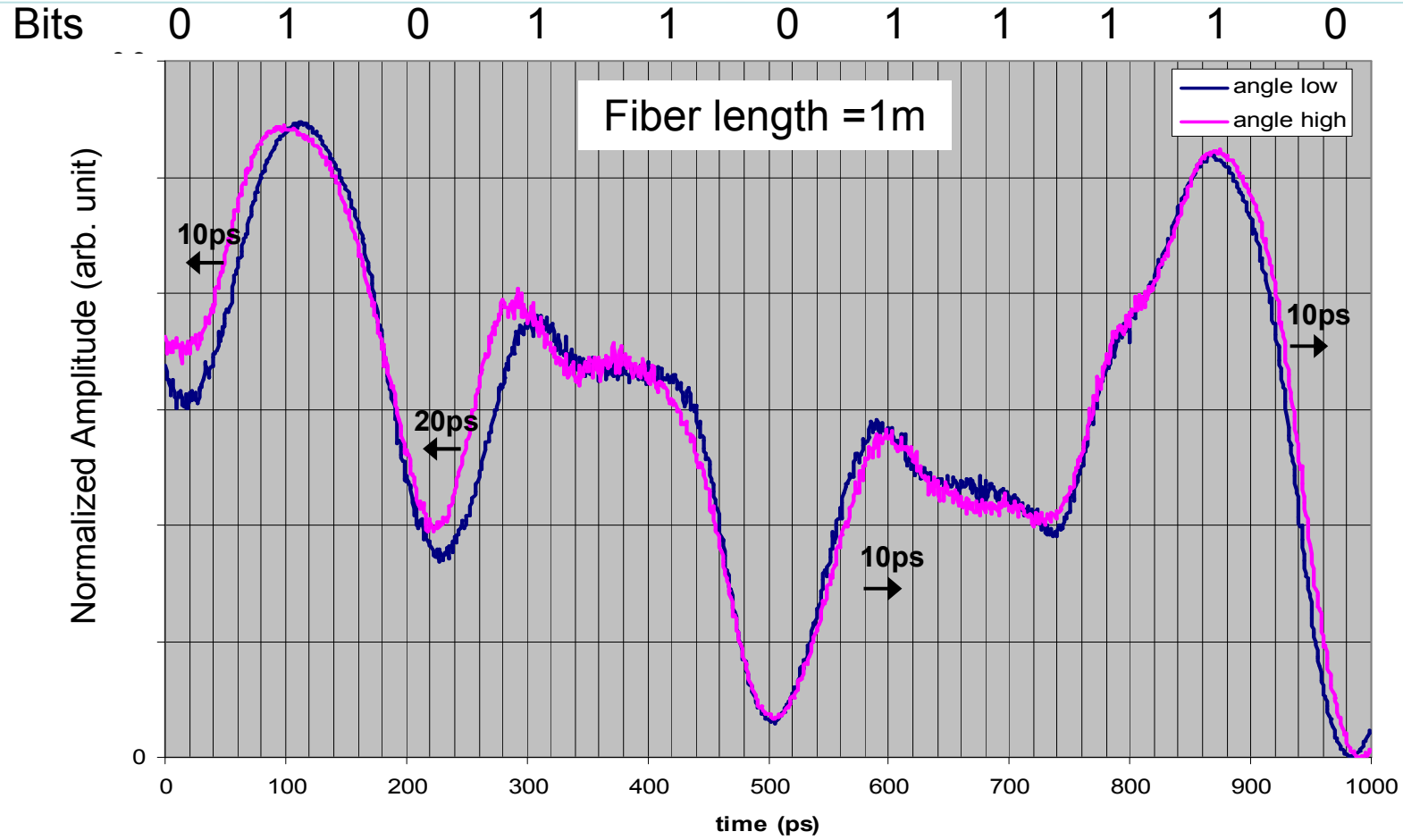
# Angle and Radial Offset Dependence

Fiber length = 1m



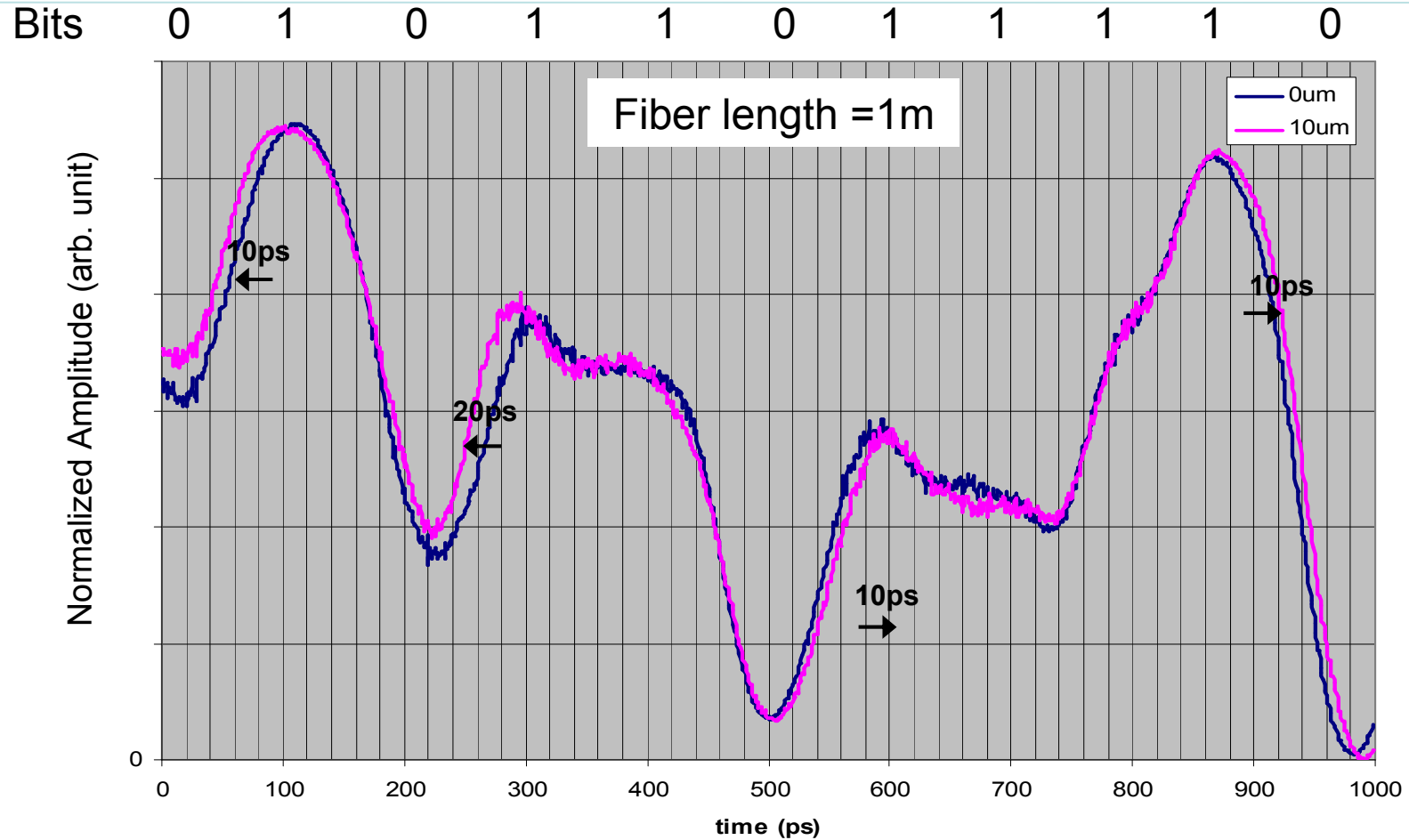
The temporal delay or “phase lag” is similar for higher radial offsets and higher angular offsets

# Pattern A (Angle Dependence)



The relative delay or “phase lag” of the VCSEL modes depends on the bit sequence

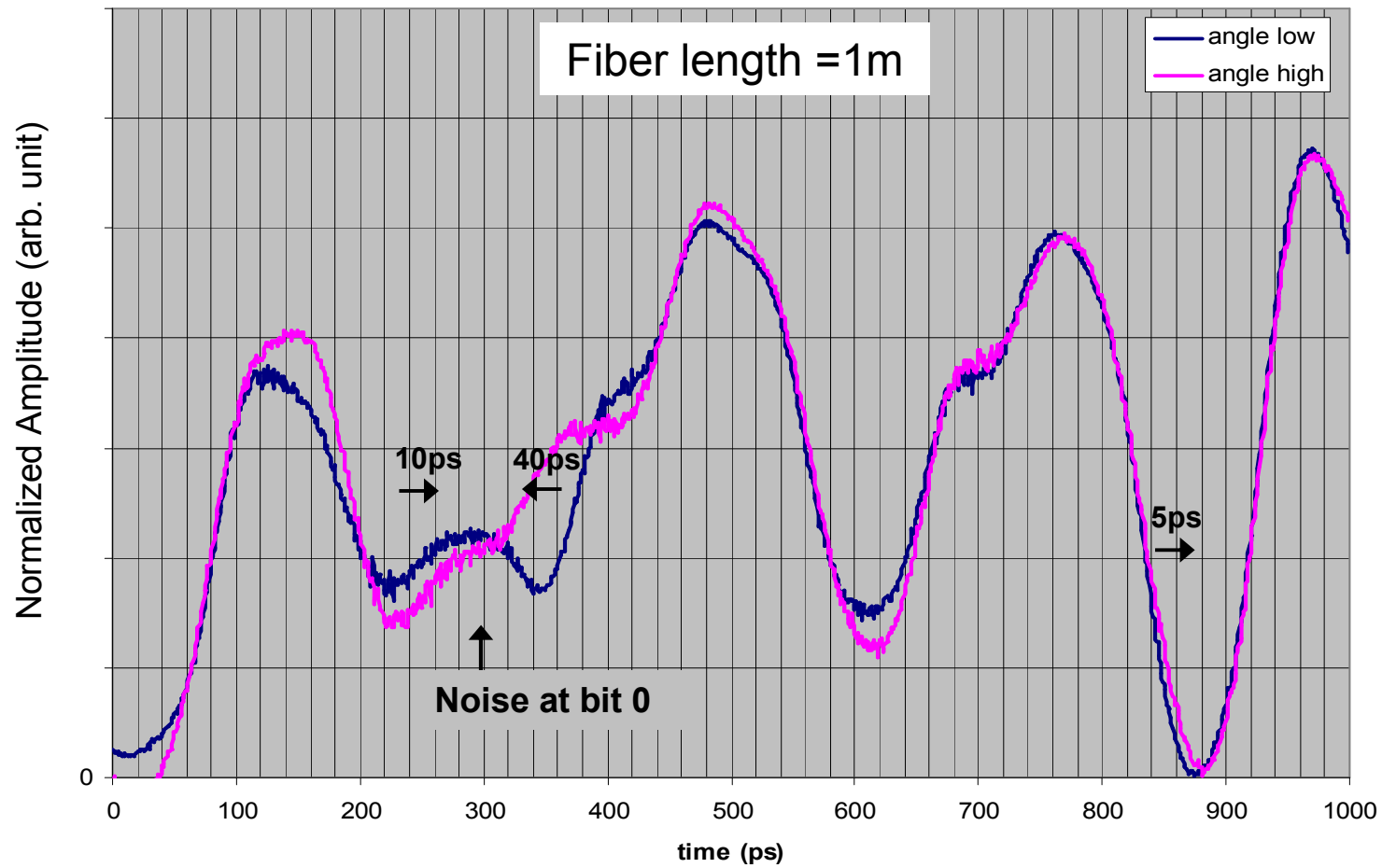
# Pattern A (Radial Offset Dependence)



- The relative delay of the VCSEL modes show similar dependence on radial and angular offsets.
- There is a finite and noticeable delay between when the VCSEL modes are turned “on and off”

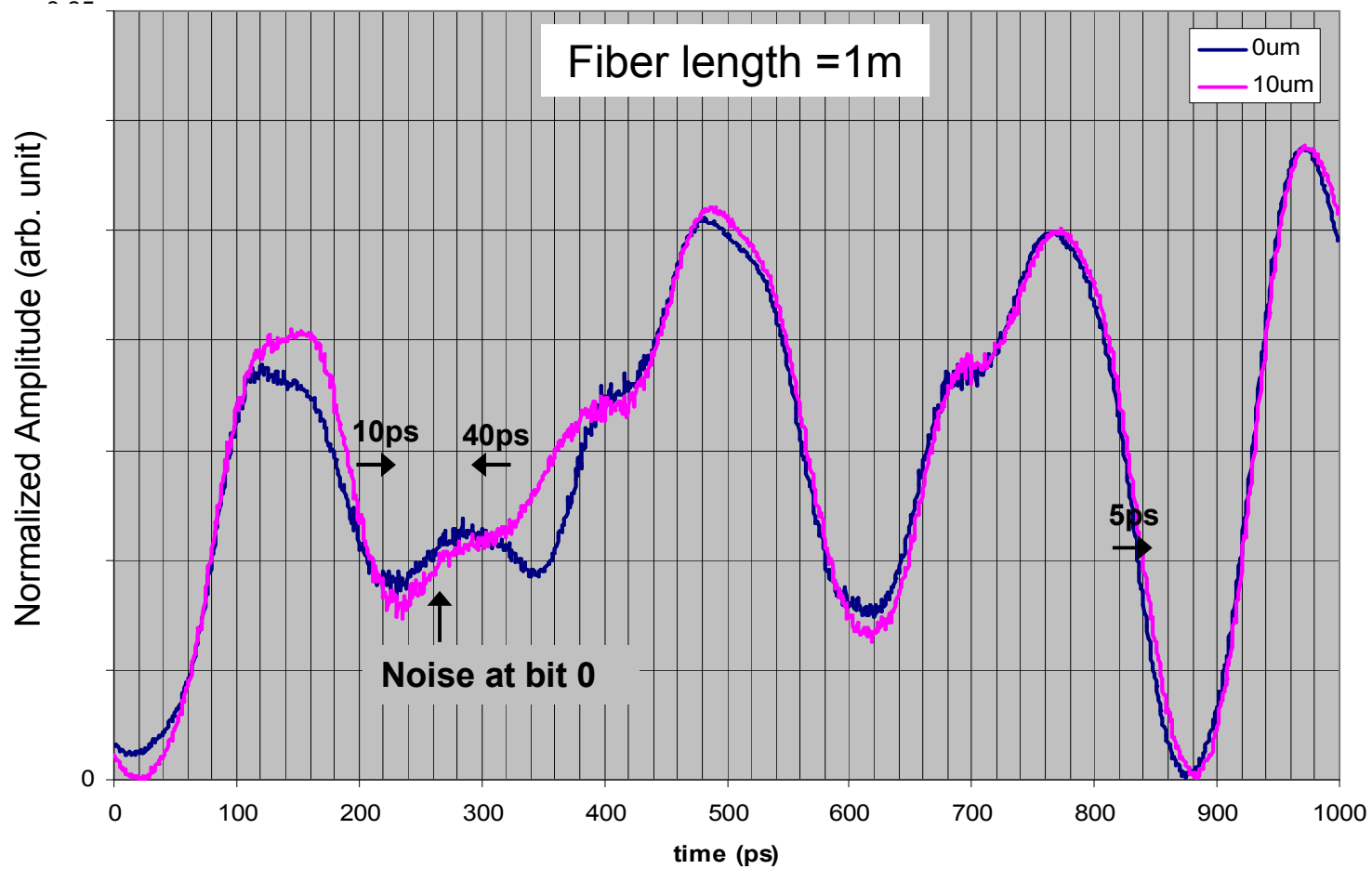
# Pattern B (Angle Dependence)

Bits 0 1 0 0 1 1 0 1 1 0 1



# Pattern B (Radial Offset Dependence)

Bits 0 1 0 0 1 1 0 1 1 0 1



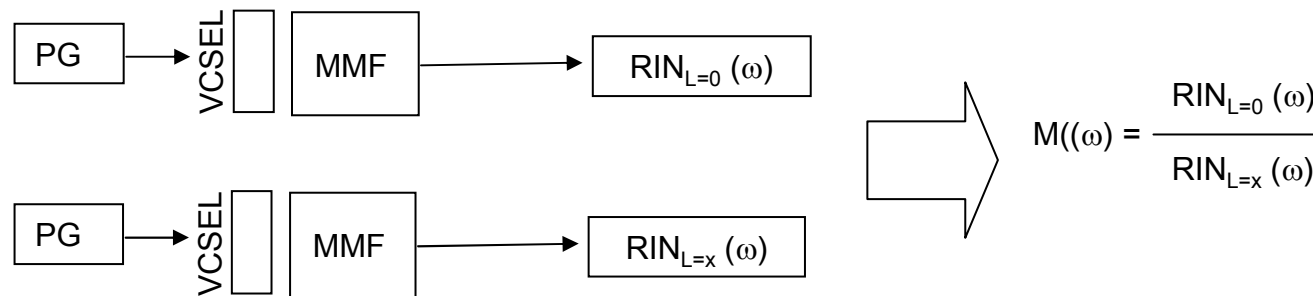
## Summary

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- The relative delay of the VCSEL modes show similar dependence to radial offsets and angular offsets.
- The relative delay of the VCSEL modes depends on the bit sequence
- The occurrence of the observable LMD is limited to a few bits in a long PRBS, and therefore the BER shoulder related to the effect remains below  $BER \sim 10E-8$
- There is a finite and noticeable delay in VCSEL modes “on and off” and there is a spatial dependence
- The relative delay can be up to 20-40ps and impact the signal irrespective of the fiber length
- MPN has a square law dependence on the source spectral width, and radial dependence of spectral width may translate into increased modal noise in the different mode groups of the MMF



## Further Measurements



- $RIN_{L=0}(\omega)$  is measured at with a very short length of MMF , such that the “anti-correlation” of the noise in individual competing VCSEL modes are maintained
- RIN measurement is repeated with sufficiently long length (X) of MMF, so the anticorrelation of the noise in the modes are lost due to the temporal separation caused by the DMD
- M can be used as a measure of MPN

## Concluding remarks

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- Recent research shows spatial hole burning effect increases the MPN among modes that overlaps spatially
- Simulations based on spatial hole burning also confirm that there are significant delays in the gain switching of different transverse modes and the delays depend on electrode configurations
- May be it would be possible to design the electrodes and cavity to reduce the overlap of the transverse modes and possibly reduce the MPN
- In the frequency domain, radial dependence of RIN can be applied to characterize mode power fluctuations in individual modes
- Radial dependent measurements of RIN, LMD, spectral width may be used to characterize VCSEL for MPN performances
- Possibly, the radial dependence can be incorporated in the existing model of MPN or k-factor for better prediction of link performance.

## References

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