DGaO 2019, Darmstadt, June 13, 2019

Physical-Optics Analysis of Optical Interferometers

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Applied Computational Optics Group

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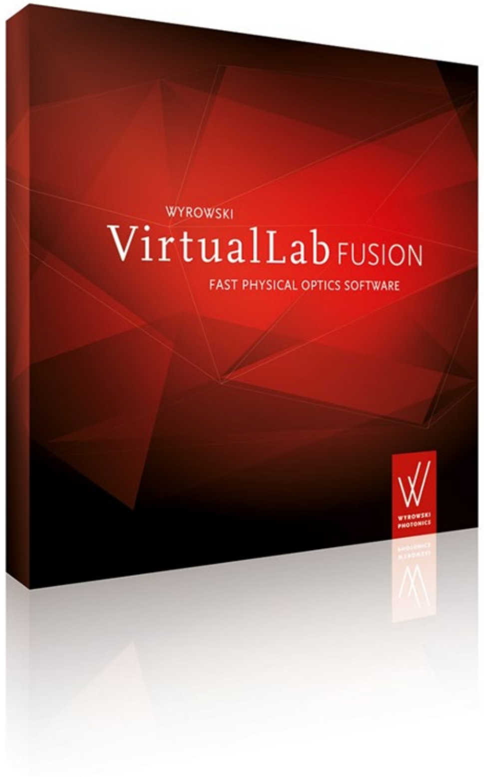
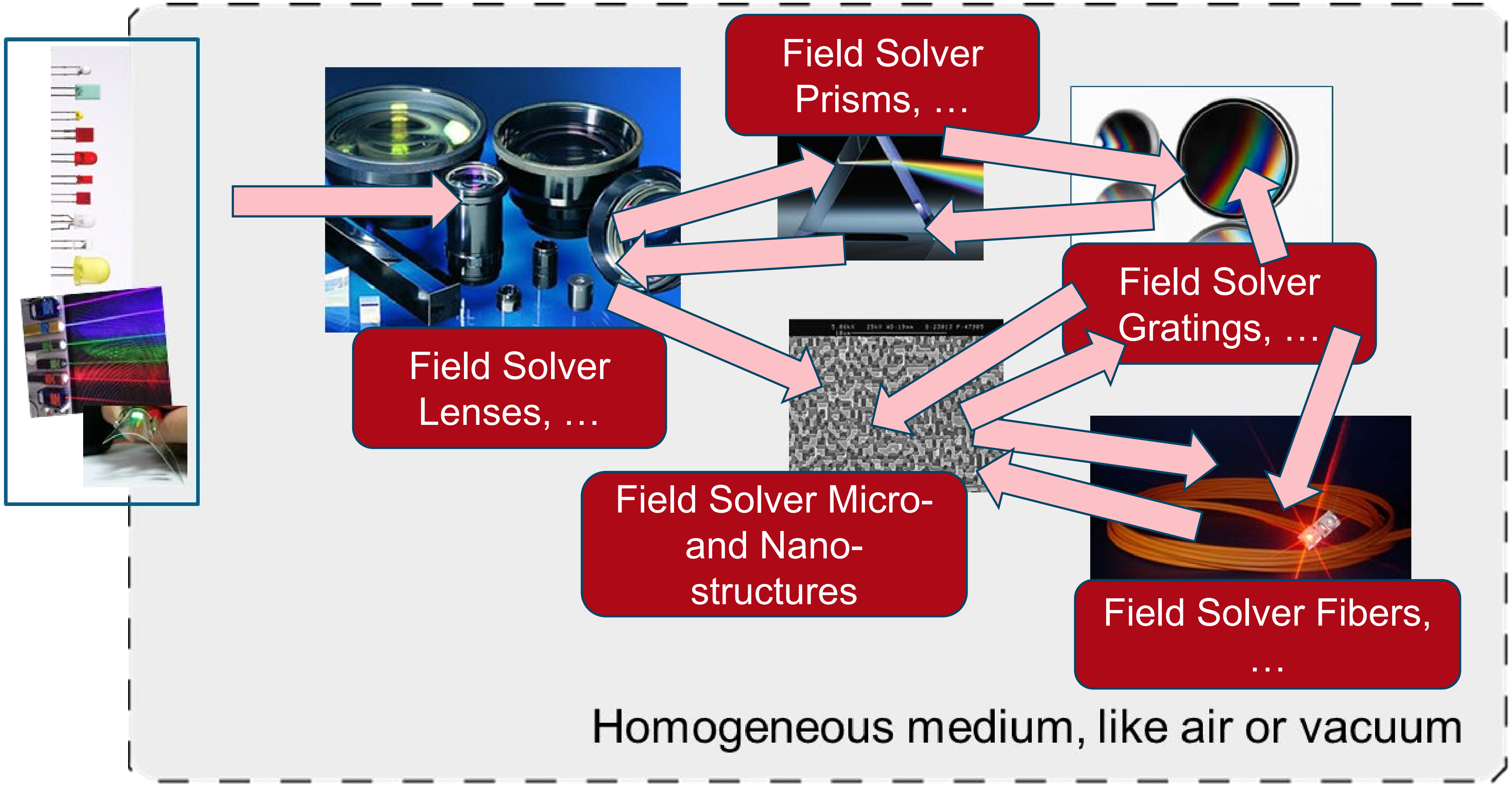
LightTrans

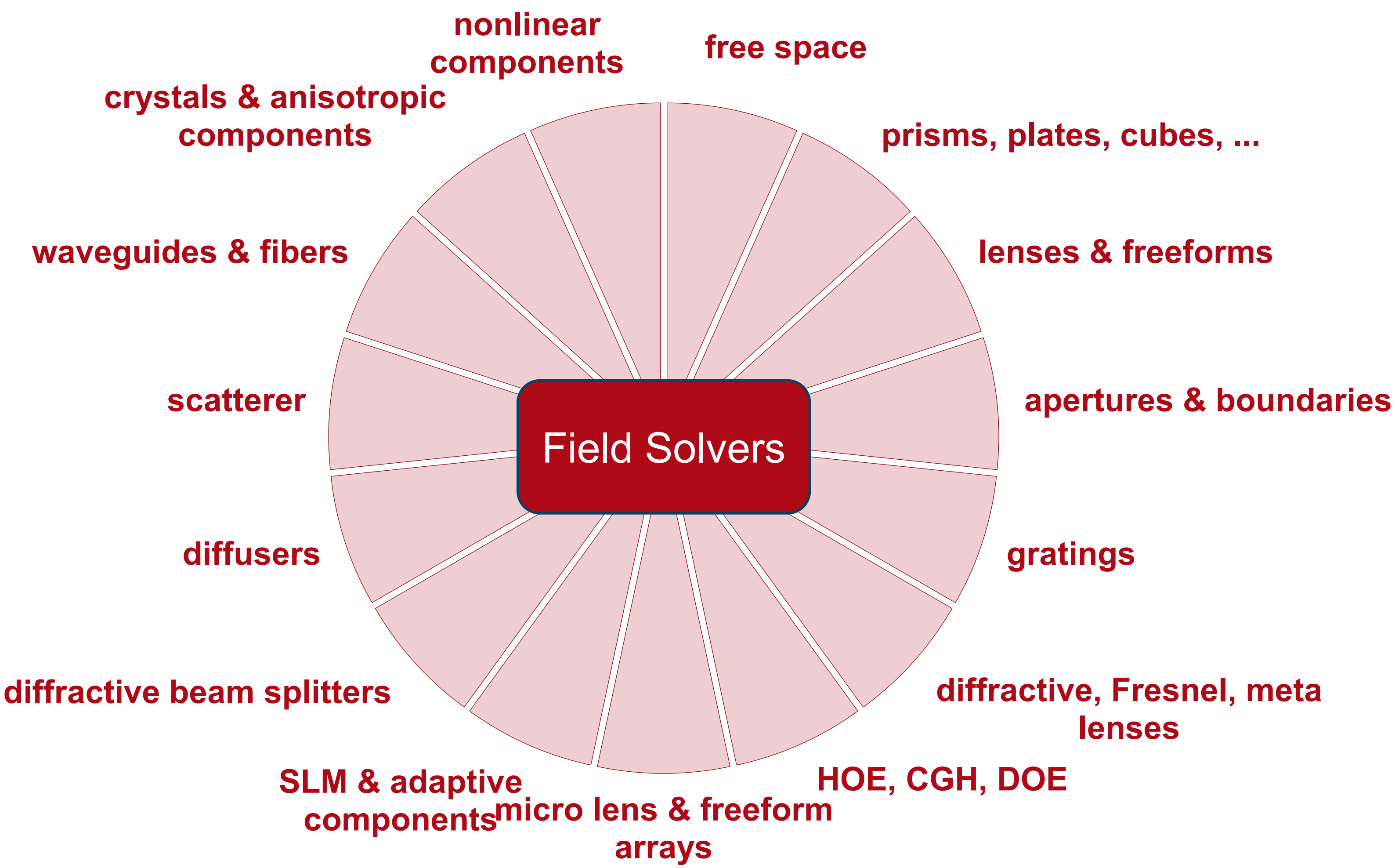


Connecting Optical Technologies

Physical-Optics System Modeling by Connecting Field Solvers

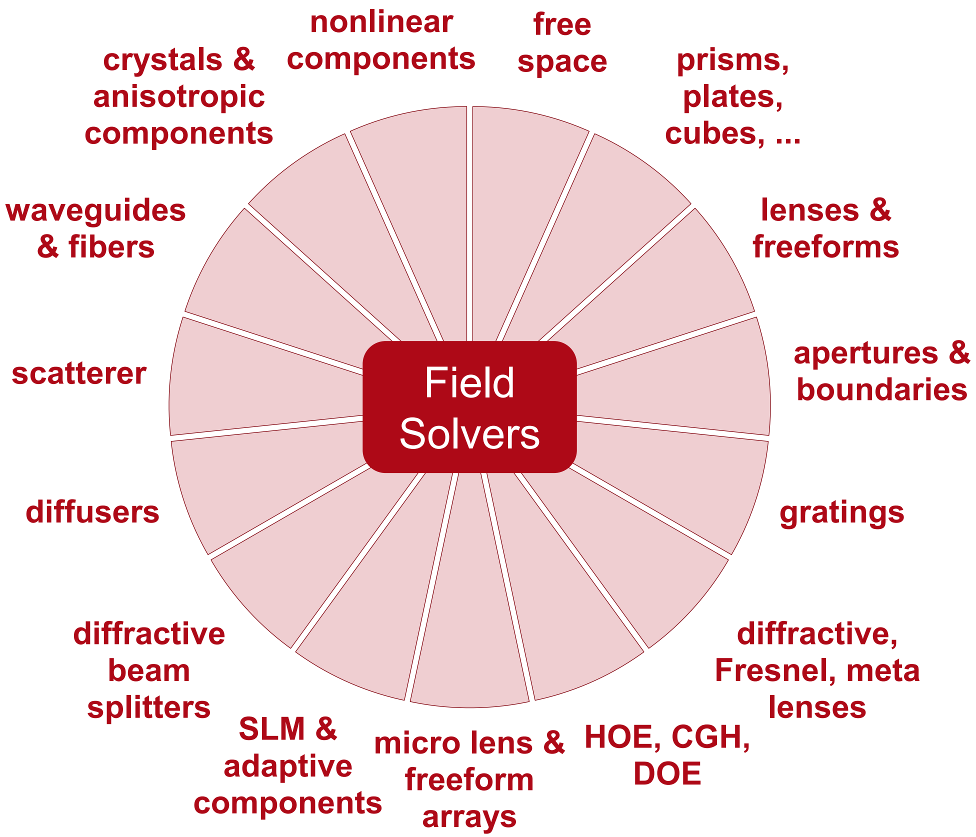


Physical-Optics System Modeling: Regional Field Solvers



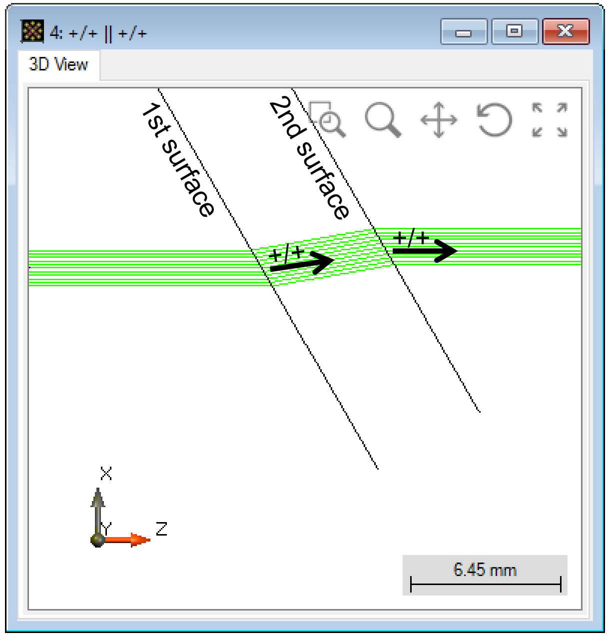
Physical-Optics System Modeling by Connecting Field Solvers

Connection of solvers via I/O channel concept which enables non-sequential physical-optics system modeling



Surface Channels: Example of Plate/Etalon

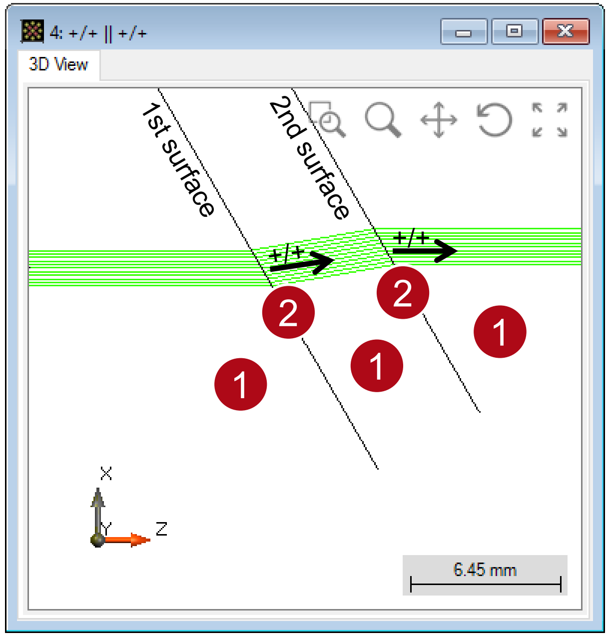
Setting A



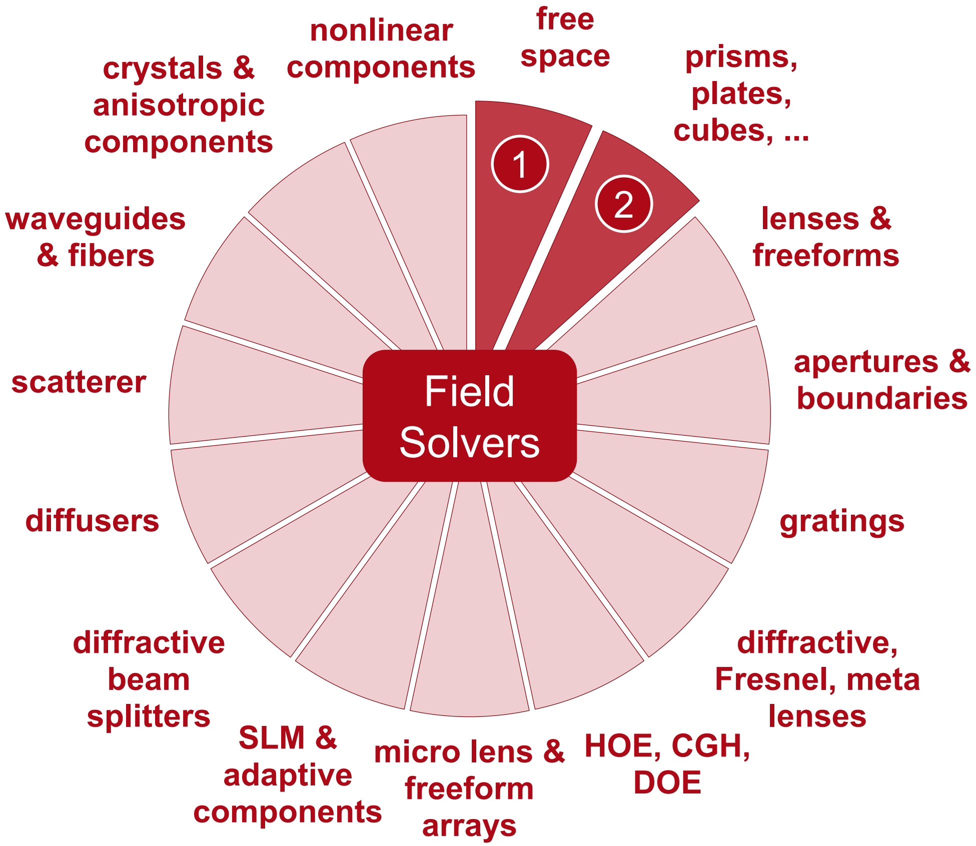
Surface	+/+	+/-	-/-	-/+
1st	×			
2nd	×			

Surface Channels: Example of Plate/Etalon

Setting A

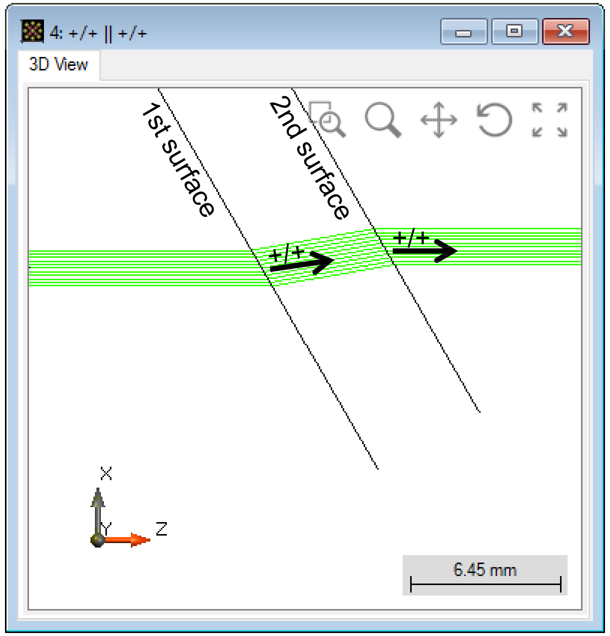


Surface	+/+	+/-	-/-	-/+
1st	×			
2nd	×			



Surface Channels: Example of Plate/Etalon

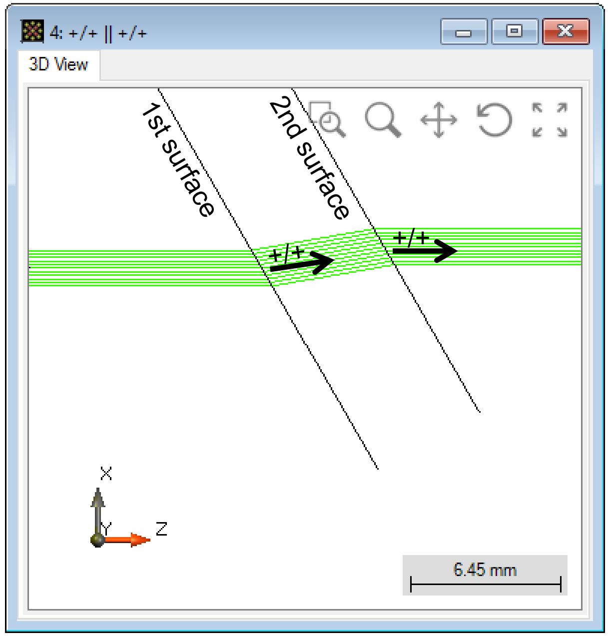
Setting A



Surface	+/+	+/-	-/-	-/+
1st	×			
2nd	×			

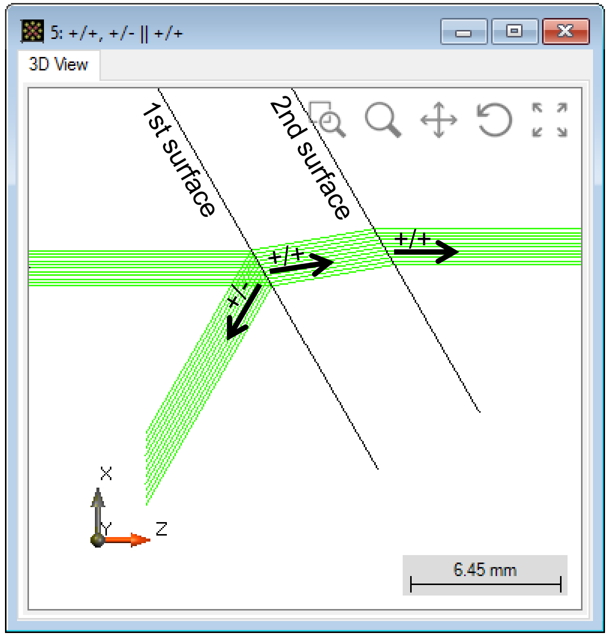
Surface Channels: Example of Plate/Etalon

Setting A



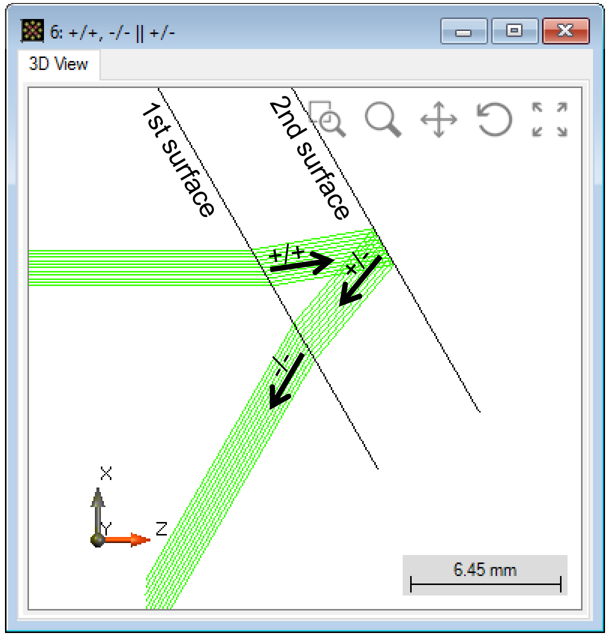
Surface	+/+	+/-	-/-	-/+
1st	×			
2nd	×			

Setting B



Surface	+/+	+/-	-/-	-/+
1st	×	×		
2nd	×			

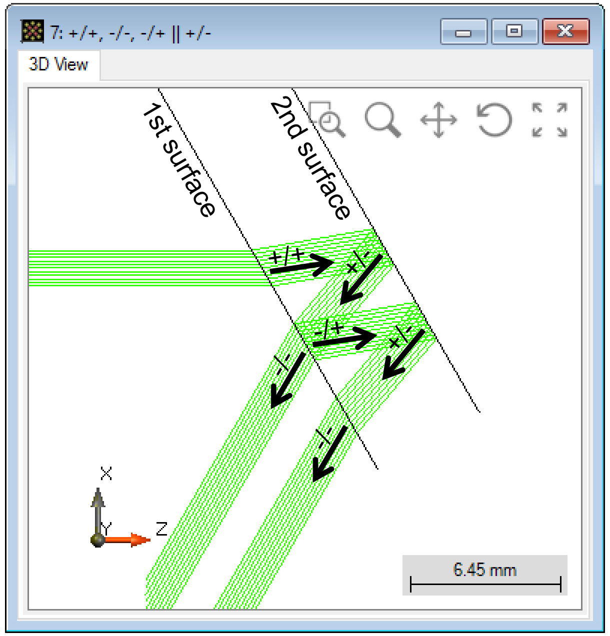
Setting C



Surface	+/+	+/-	-/-	-/+
1st	×		×	
2nd		×		

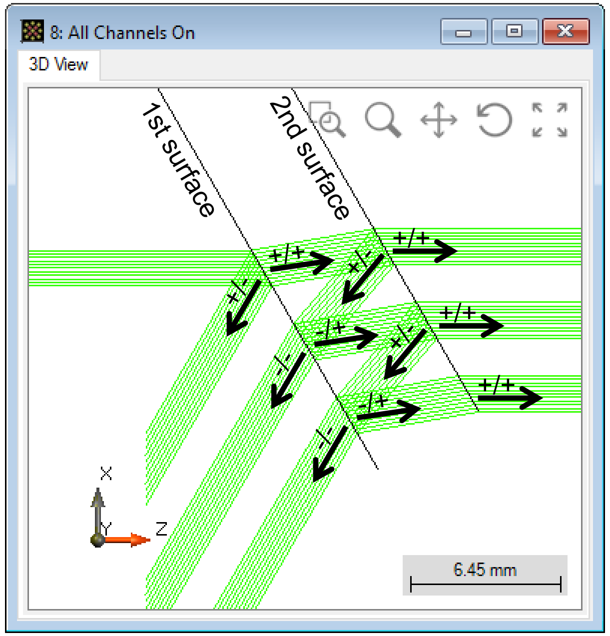
Surface Channels: Example of Plate/Etalon

Setting D



Surface	+/+	+/-	-/-	-/+
1st	×		×	×
2nd		×		

Setting E

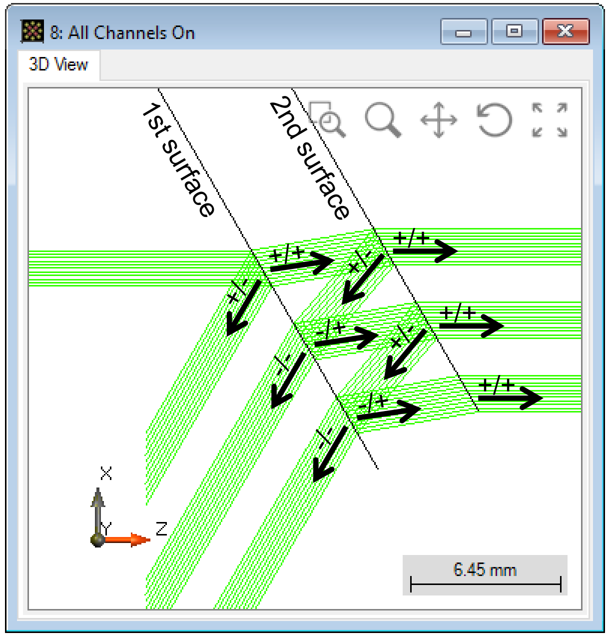


Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×

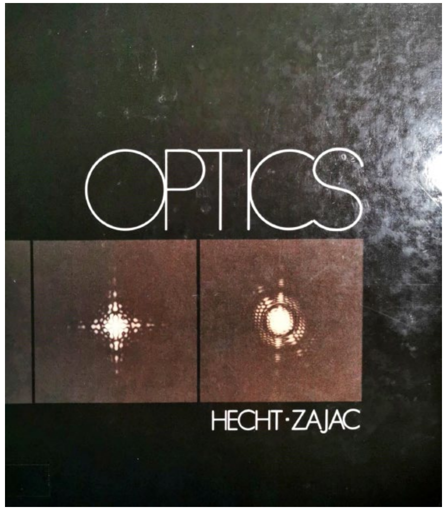
Surface Channels: Example of Plate/Etalon

planar-planar (parallel)

- **varying thickness from 100 to 99 μm**



Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×



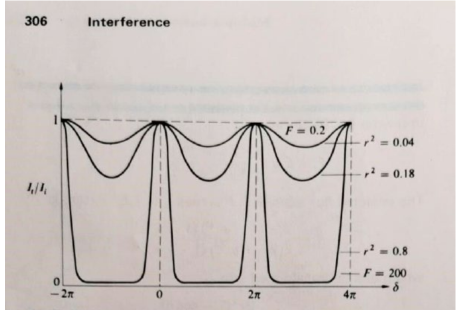

306 Interference

Fig. 9.45 Airy function.

density emerging from the film. It follows from Eqs. (9.33) and (9.34), that this is indeed the case, that is

$$I_i = I_r + I_t. \quad (9.35)$$

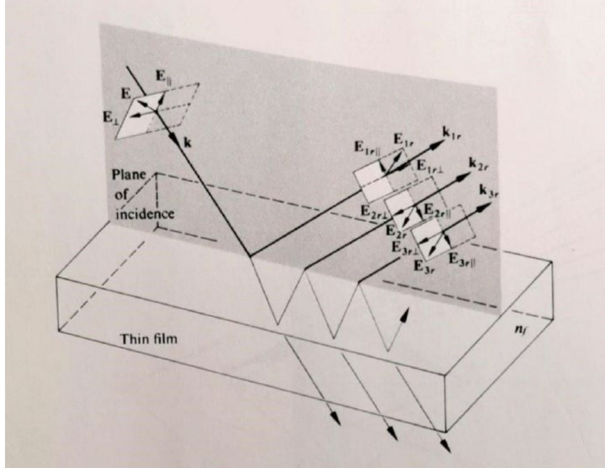


Fig. 9.41 Phase shifts arising purely from the reflections (internal $\theta_i < \theta_p'$).

at point P, is then

$$E_{0r} = E_0 r - (E_0 trt' + E_0 tr^3 t' + E_0 tr^5 t' + \cdots)$$

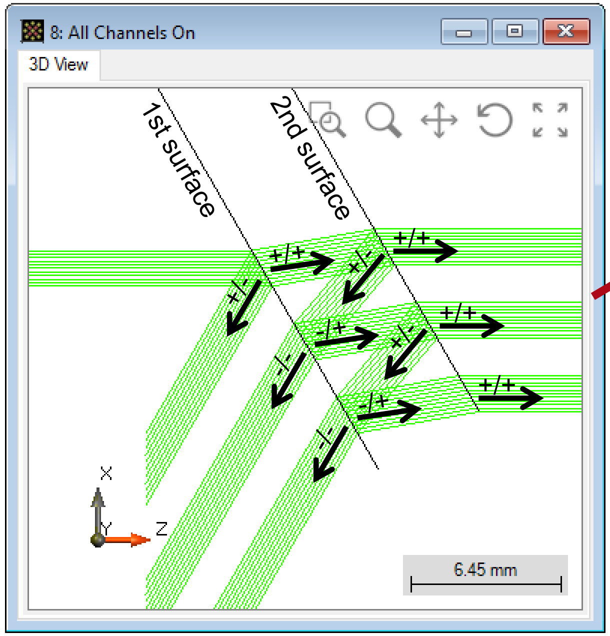
or

$$E_{0r} = E_0 r - E_0 trt'(1 + r^2 + r^4 + \cdots),$$

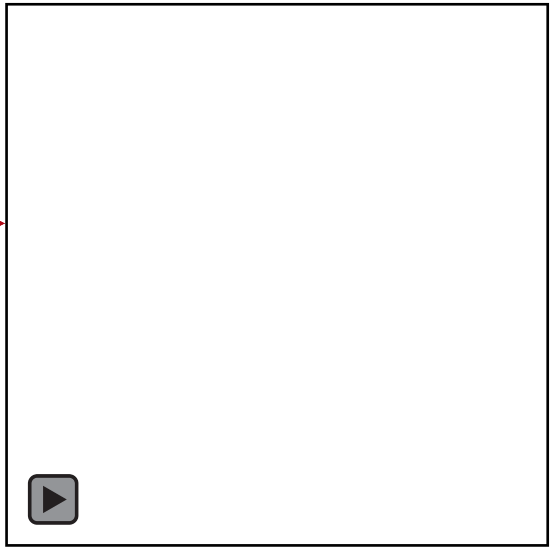
Surface Channels: Example of Plate/Etalon

planar-planar (parallel)

- **varying thickness from 100 to 99µm**



Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×



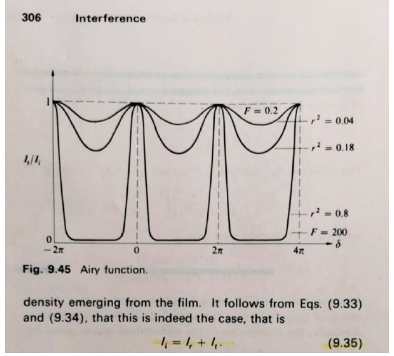

306 Interference

Fig. 9.45 Airy function.

density emerging from the film. It follows from Eqs. (9.33) and (9.34), that this is indeed the case, that is

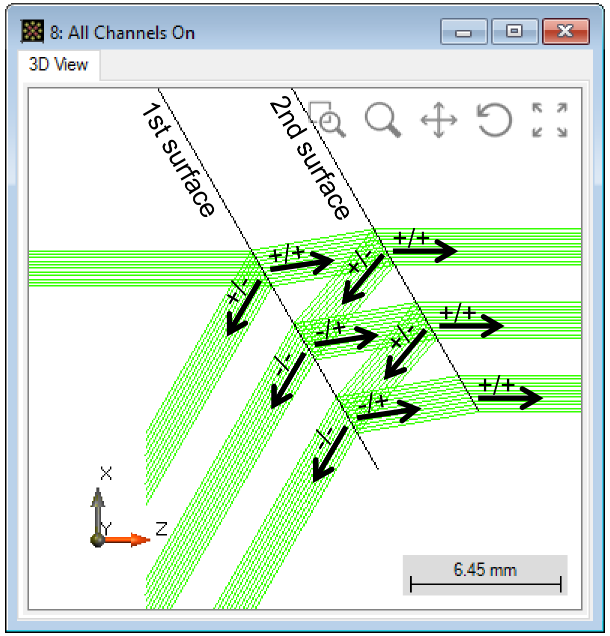
$$I_i = I_r + I_t \quad (9.35)$$

Constructive and destructive interference alternatively shows up when the thickness of plate varies.

Surface Channels: Example of Plate/Etalon

planar-planar (non-parallel)

- center thickness 100 µm
- **tilt of first surface**

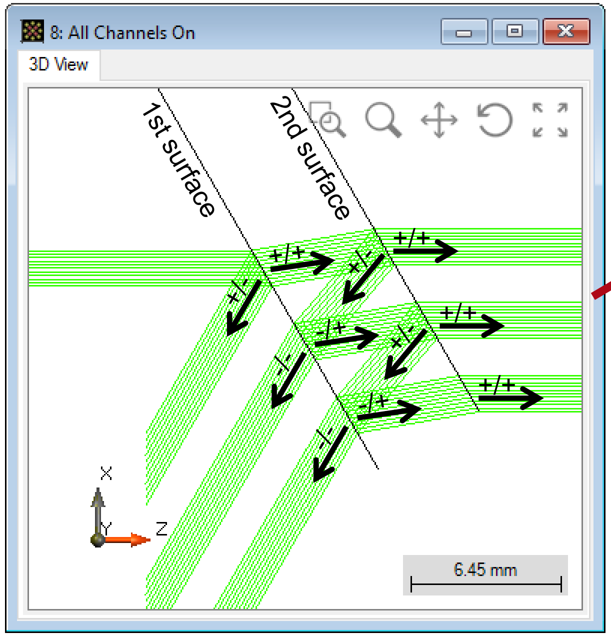


Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×

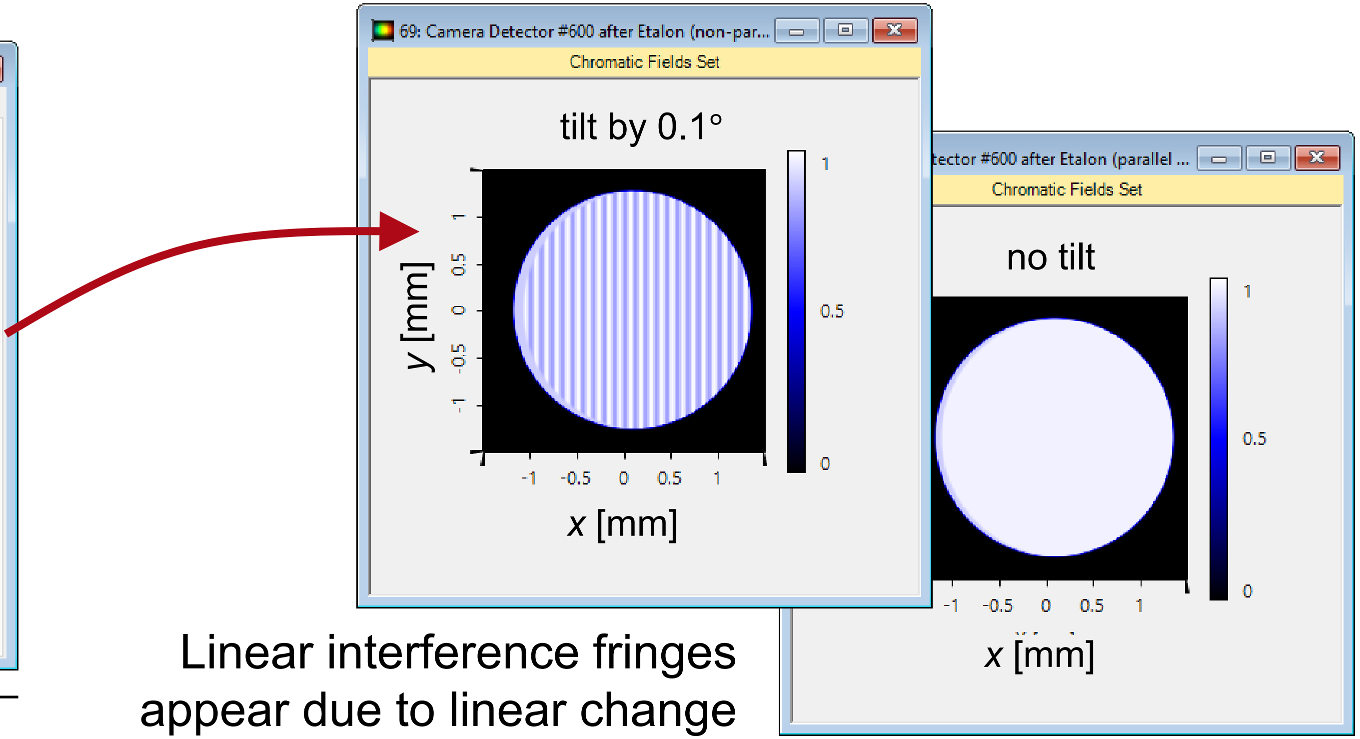
Surface Channels: Example of Plate

planar-planar (non-parallel)

- center thickness 100 µm
- **tilt of first surface**



Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×

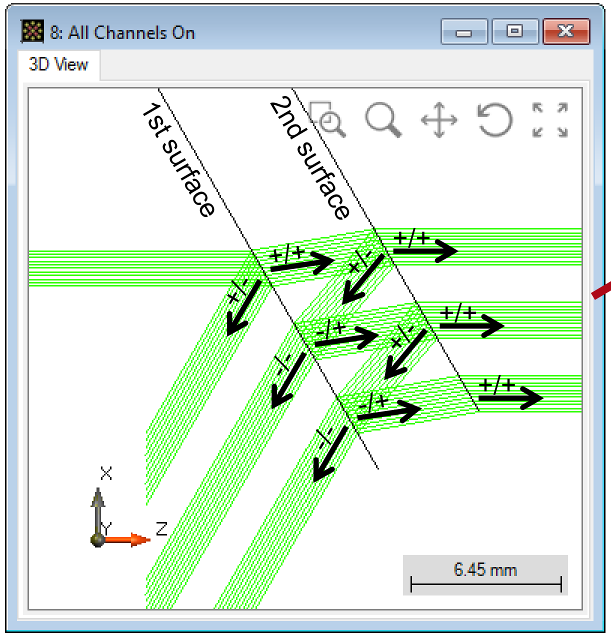


Linear interference fringes appear due to linear change of etalon thickness.

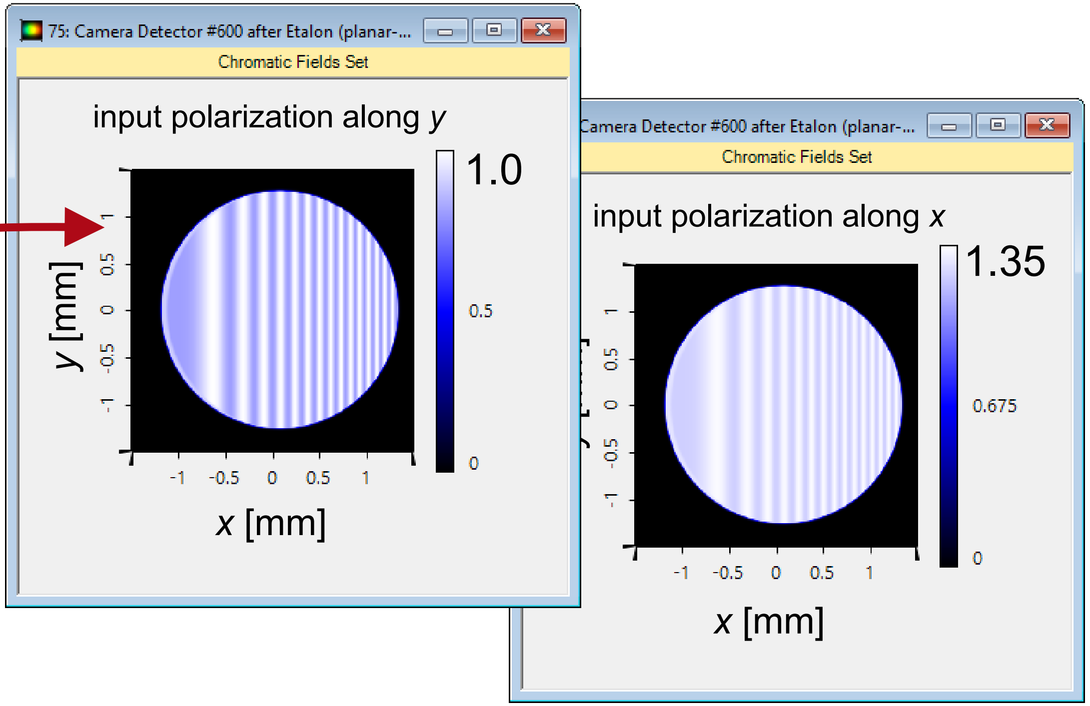
Surface Channels: Example of Plate

cylindrical-planar

- center thickness 100 µm
- **cylindrical surface radius 1 m**



Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×

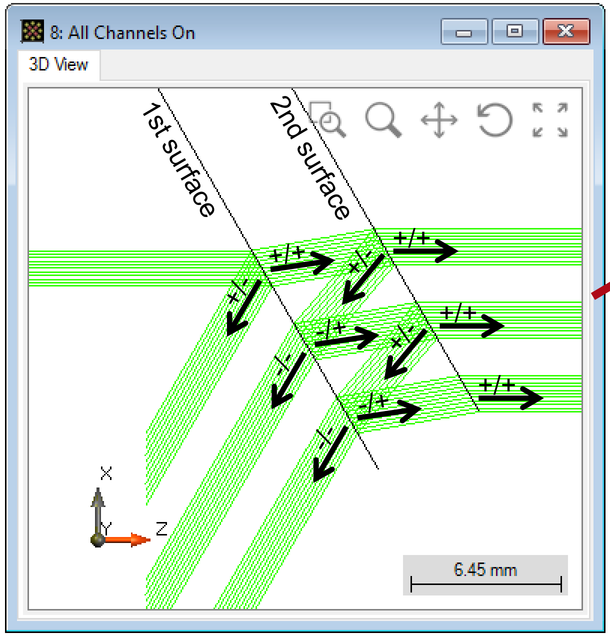


Polarization-dependent effect on the interference is considered.

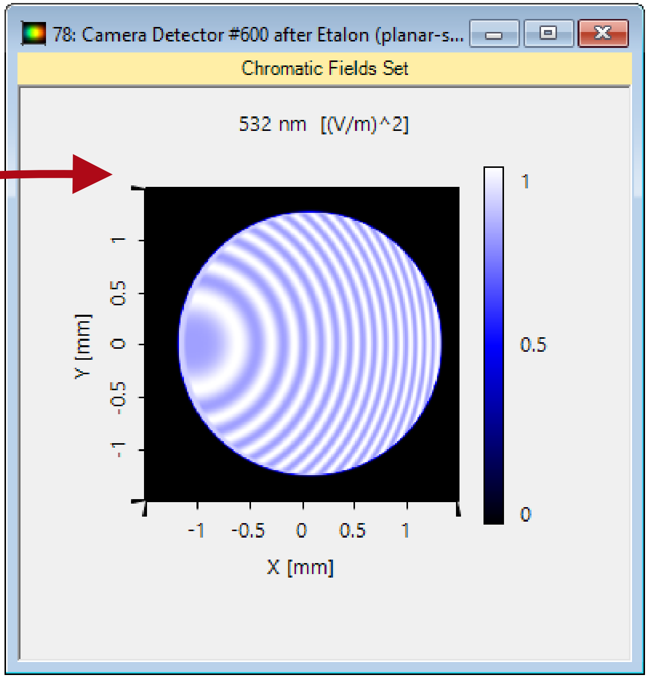
Surface Channels: Example of Plate

planar-spherical

- center thickness 100 µm
- **spherical surface radius -1 m**

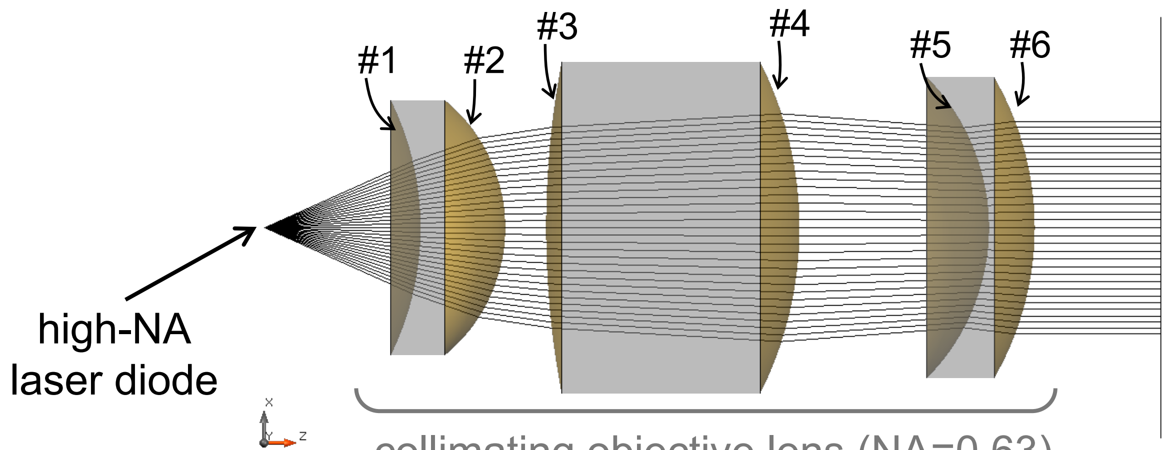


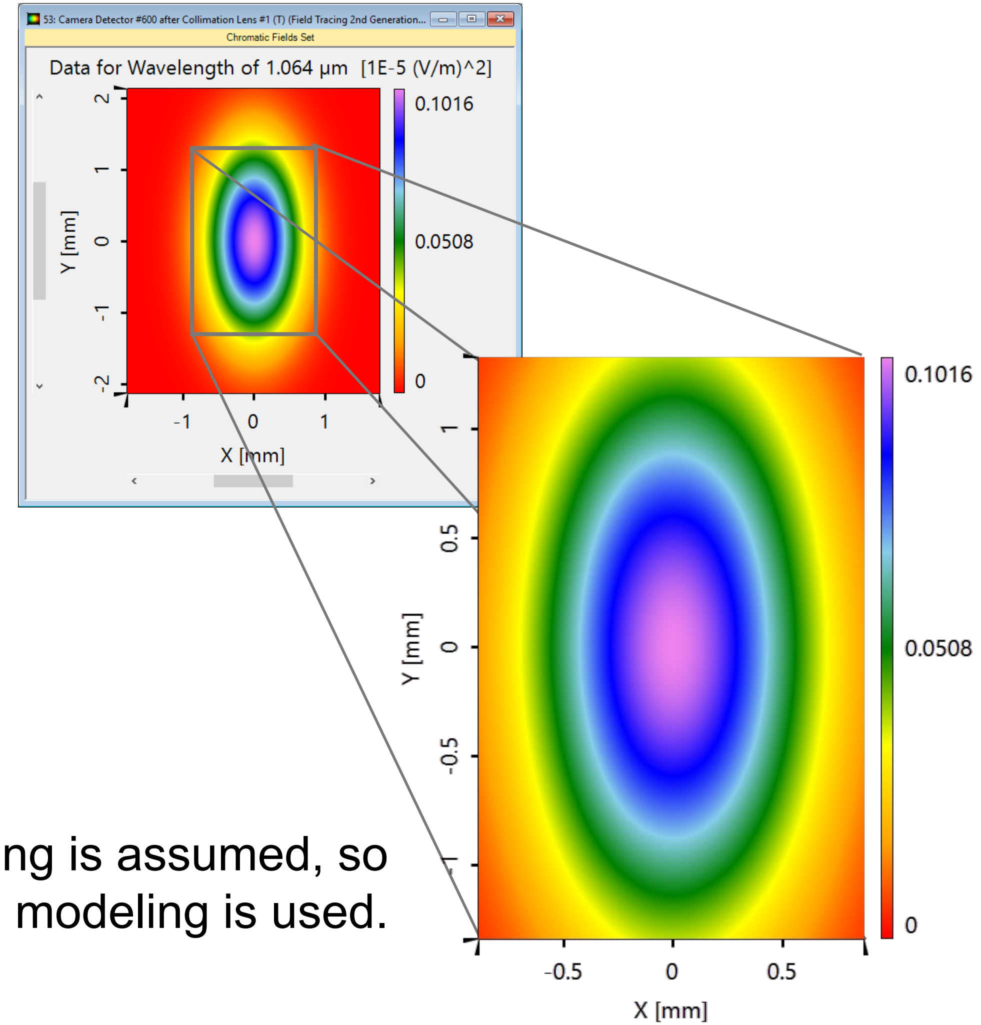
Surface	+/+	+/-	-/-	-/+
1st	×	×	×	×
2nd	×	×	×	×



Non-sequential simulation time of etalon with curved surfaces: few seconds and less

Collimation System: Sequential Simulation

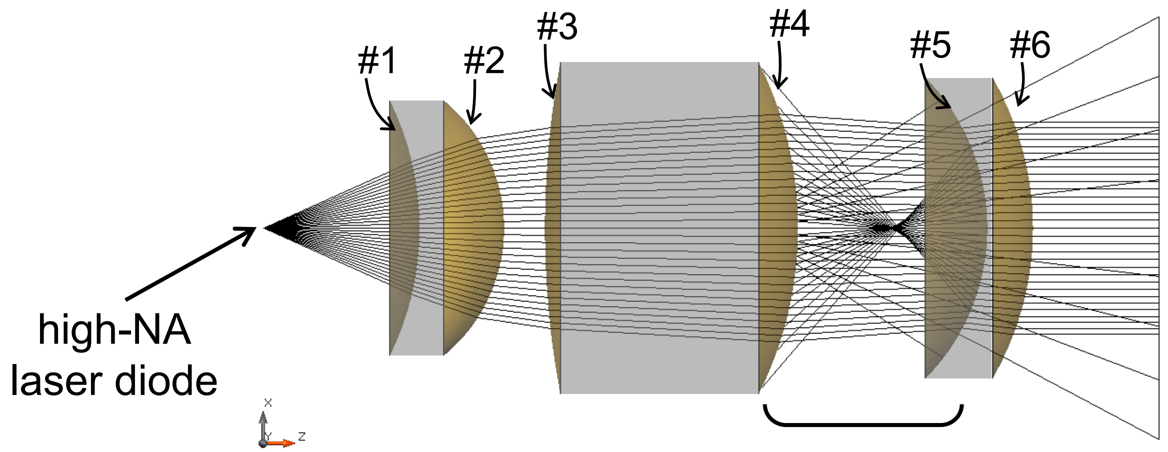




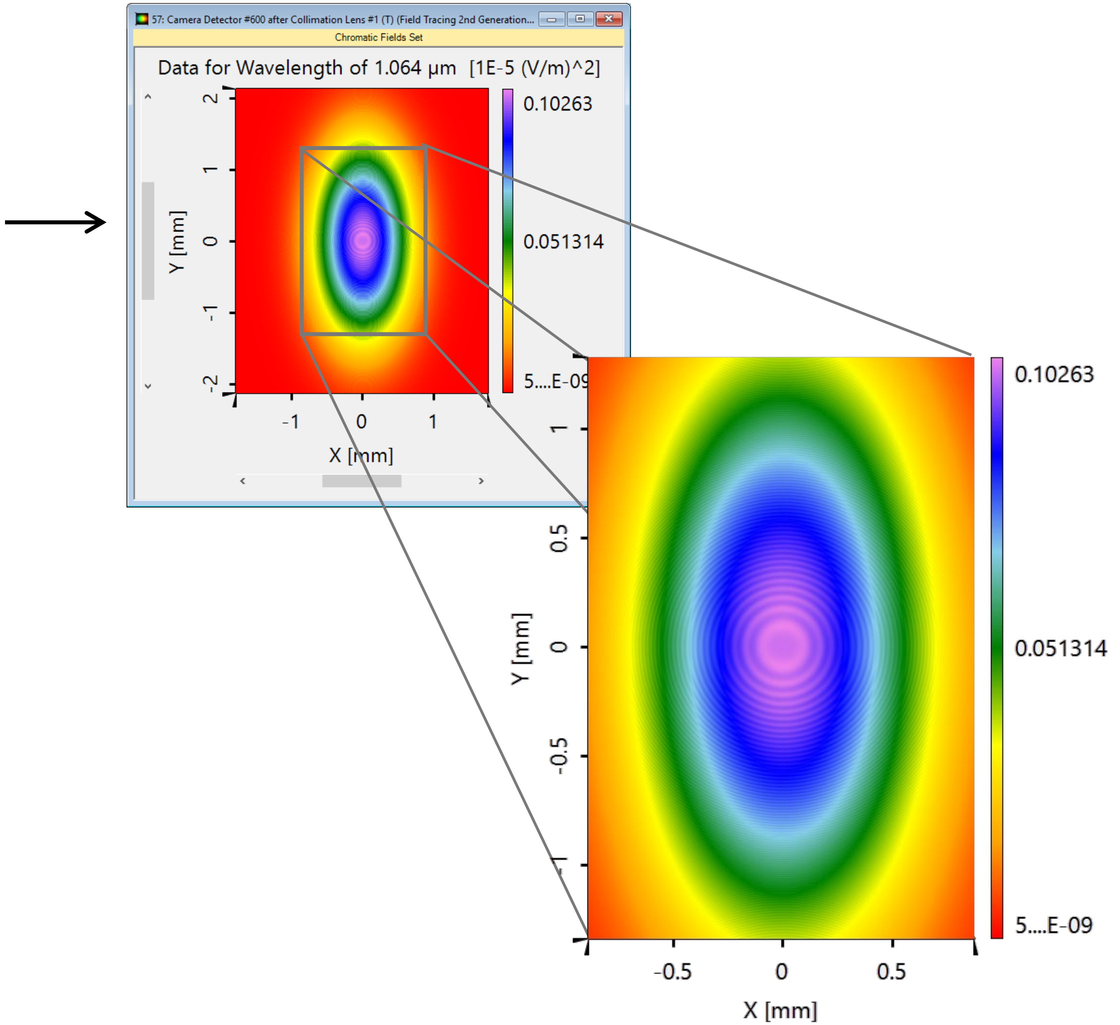
Laser Components
WSLD-1064-050m-1-PD
- fundamental Gaussian
- wavelength 1064 nm
- divergence (FWHM) 20° x 10°
- astigmatism 11.6 µm between *x*- and *y*-plane

Perfect AR coating is assumed, so sequential modeling is used.

Collimation System: Non-Sequential Simulation



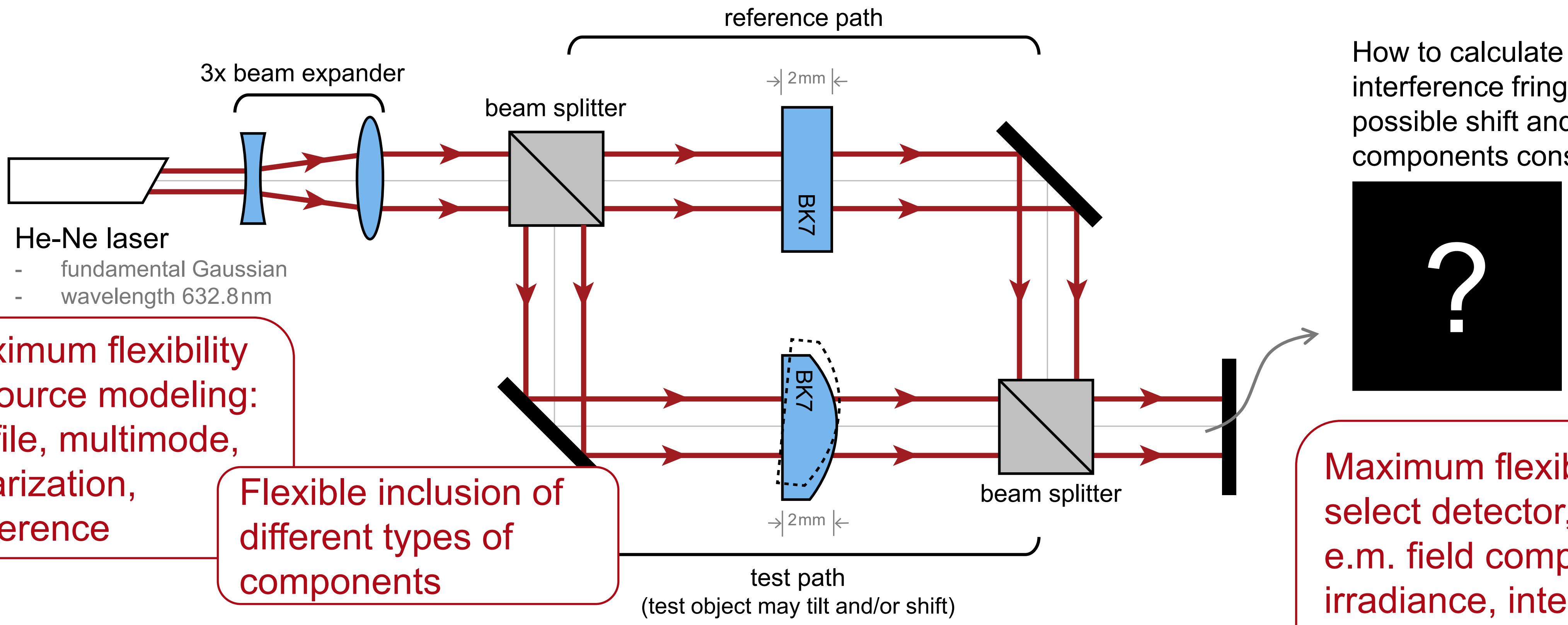
multiple reflections between uncoated surfaces #4 and #5, other surfaces are well coated.



Laser Components
WSLD-1064-050m-1-PD

- fundamental Gaussian
- wavelength 1064 nm
- divergence (FWHM) 20°x10°
- astigmatism 11.6 µm between *x*- and *y*-plane

Physical-Optics Modeling of Interferometer



How to calculate interference fringe with the possible shift and tilt of components considered?

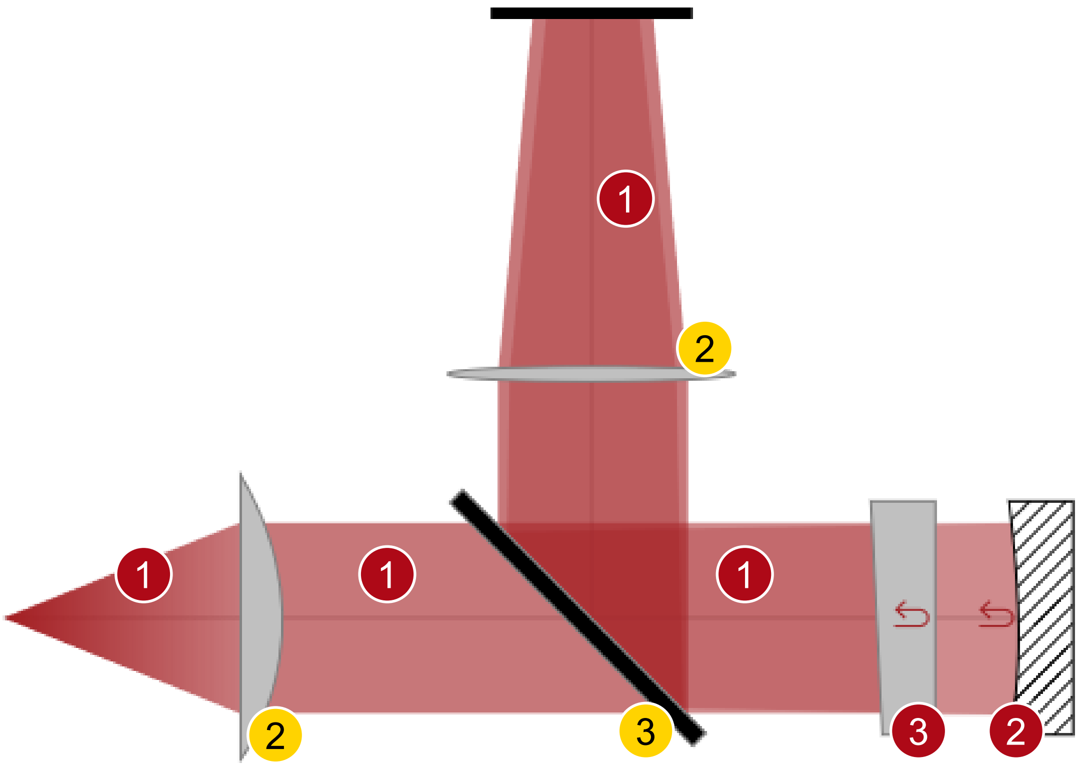
Maximum flexibility in source modeling: profile, multimode, polarization, coherence

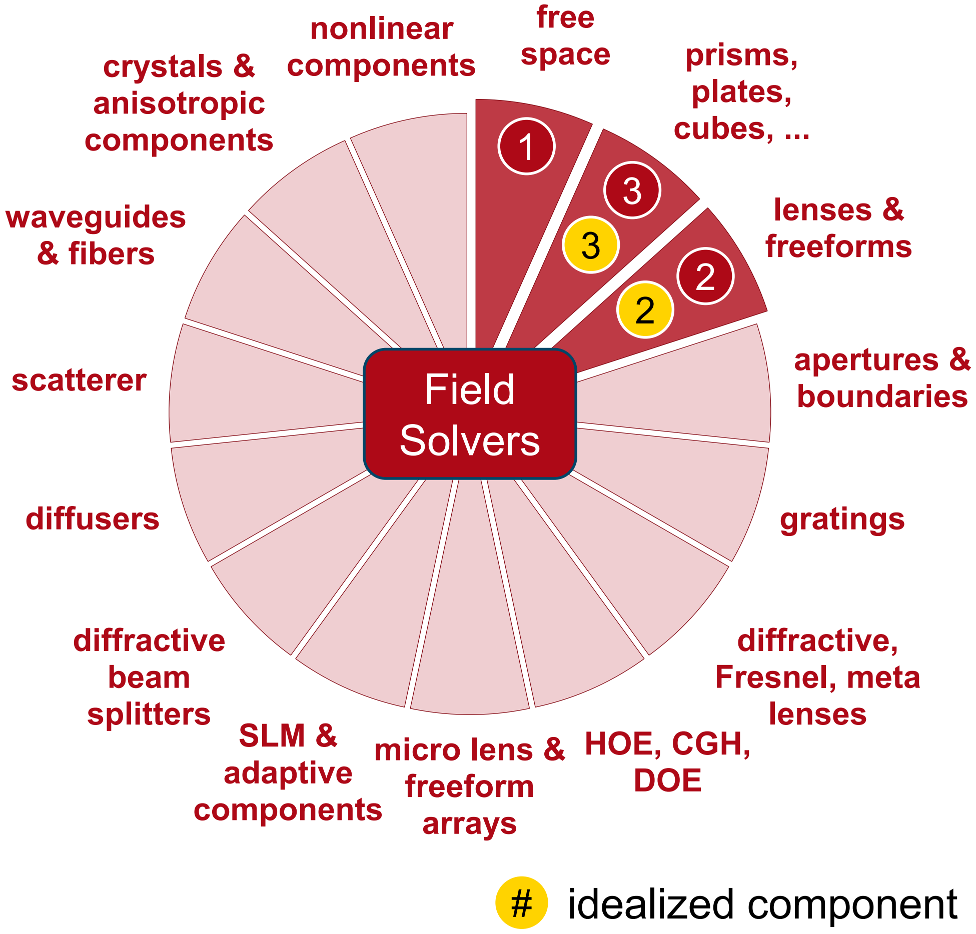
Flexible inclusion of different types of components

Maximum flexibility to select detector, e.g. e.m. field components, irradiance, intensity, polarization

Connecting Field Solvers: Example

High flexibility for different interferometer setups.



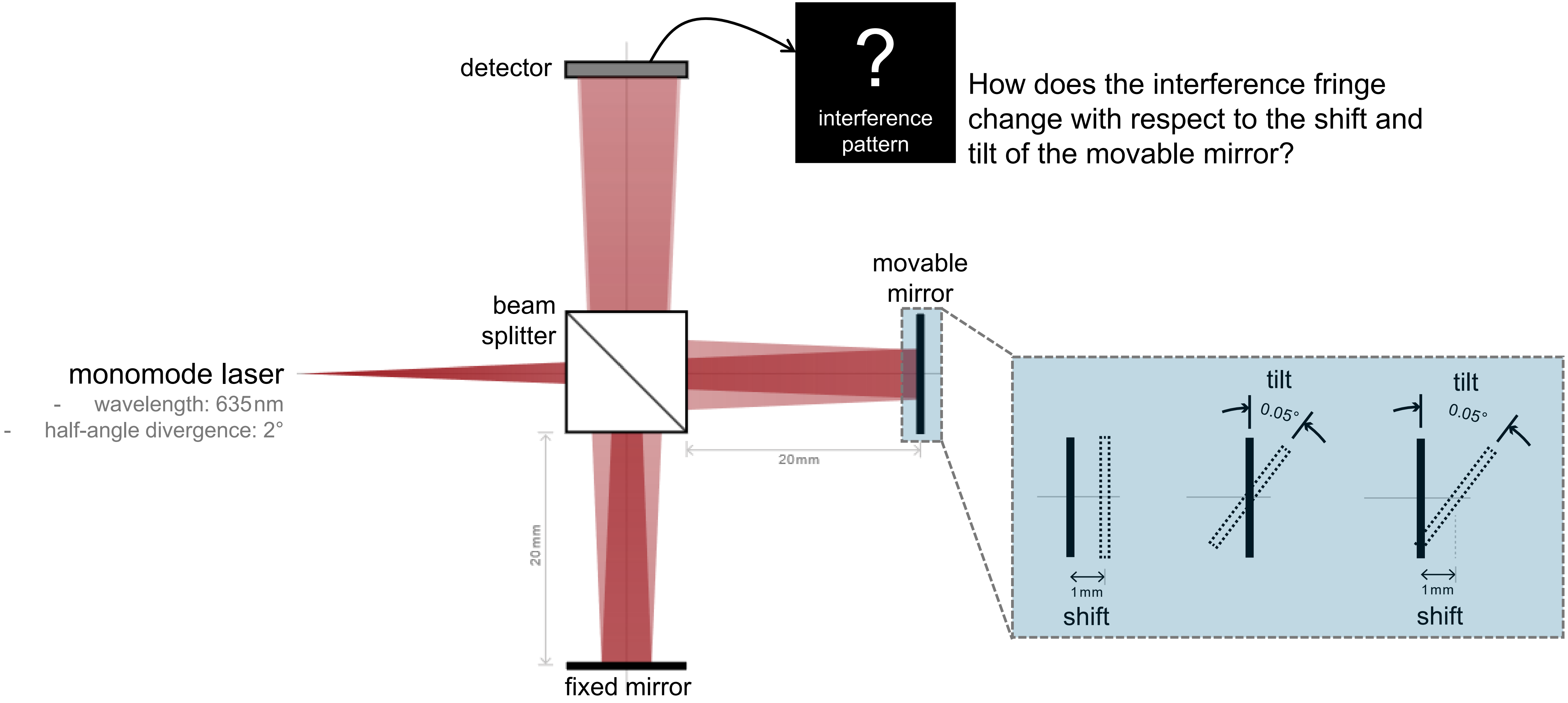


Modeling and Design Examples in VirtualLab Fusion

- Michelson interferometer
- Mach-Zehnder interferometer
- Fizeau interferometer
- Coherence measurement
- White light interferometry
- Coherence scanning interferometry
- Spectroscopy with Etalon
- Locally polarized fields by interference
- Gouy phase shift demonstration

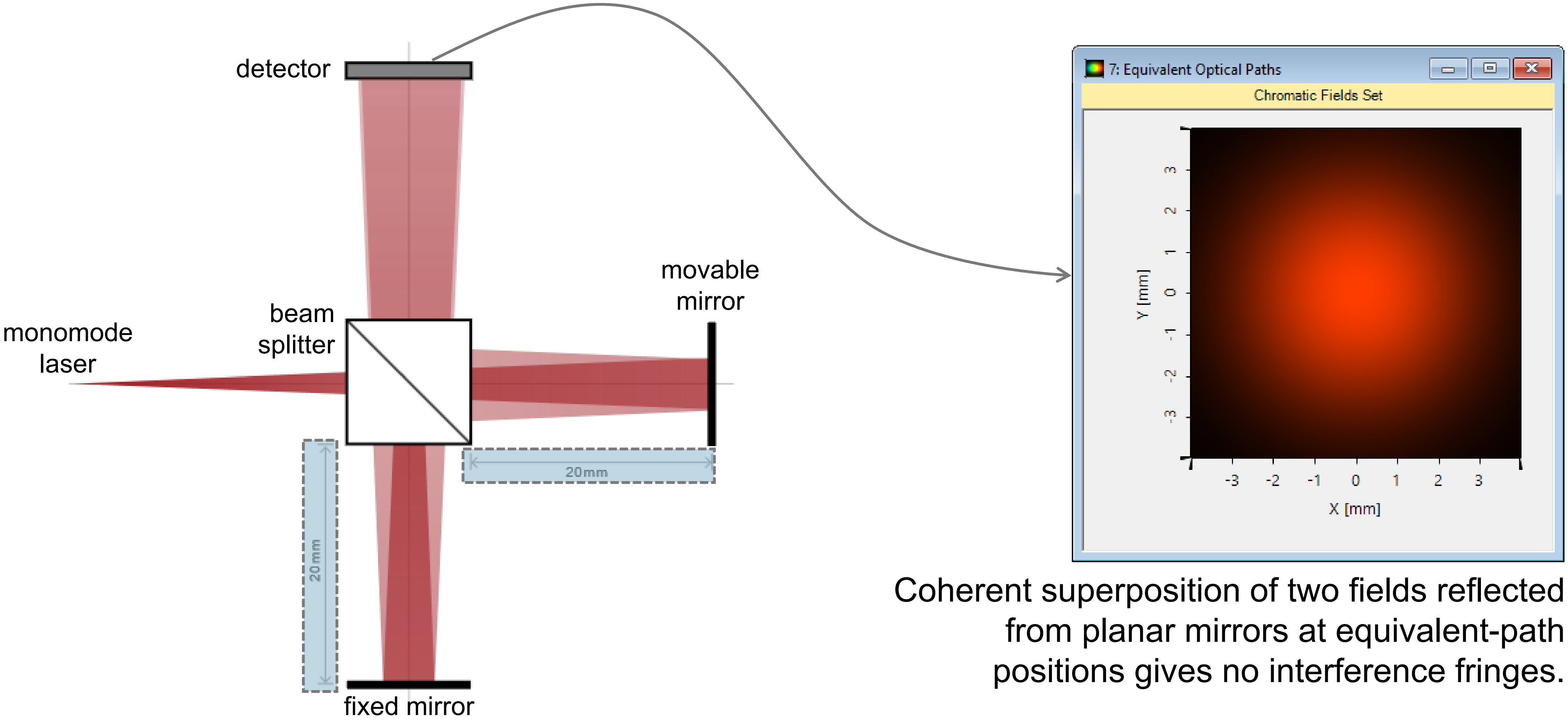
Laser-Based Michelson Interferometer and Interference Fringe Exploration

Modeling Task



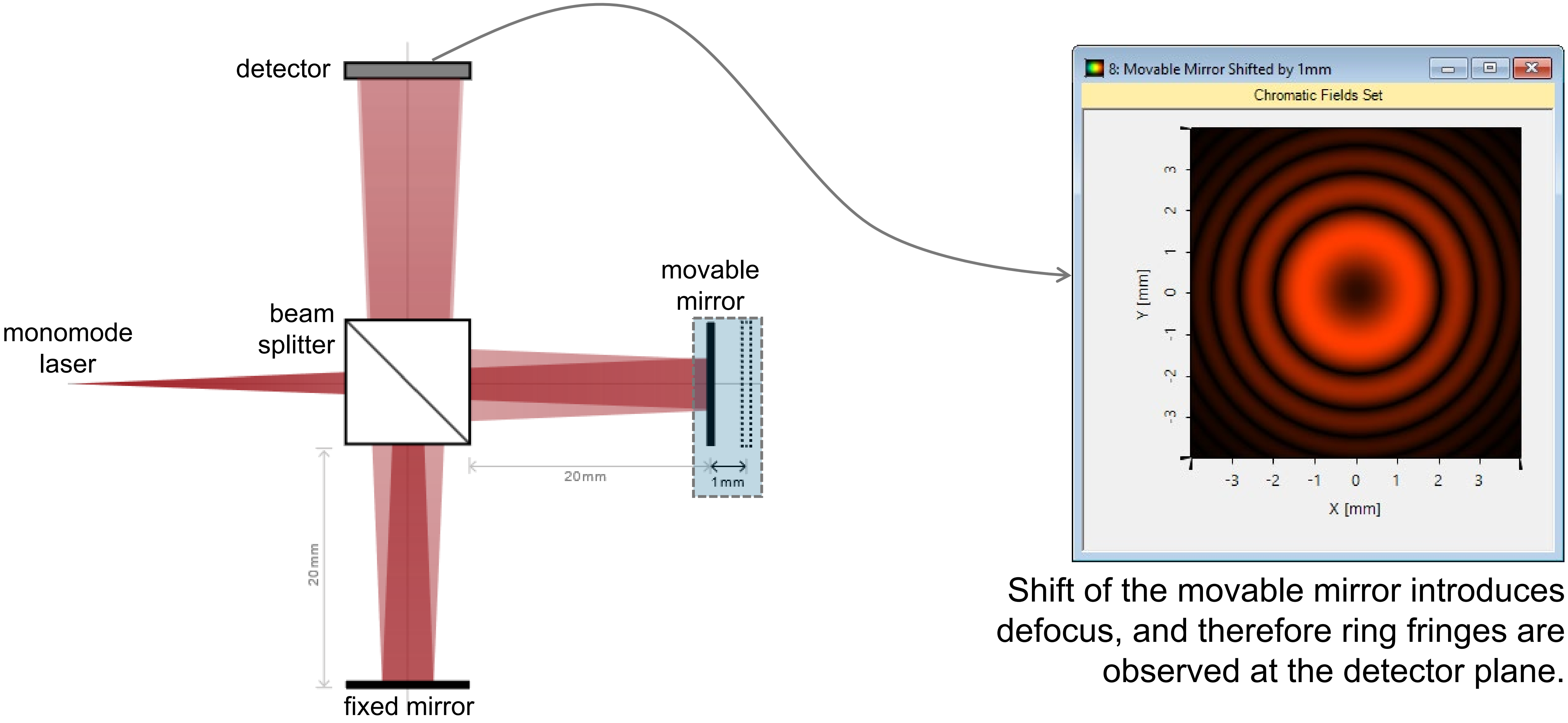
How does the interference fringe change with respect to the shift and tilt of the movable mirror?

Result with Equivalent Optical Path



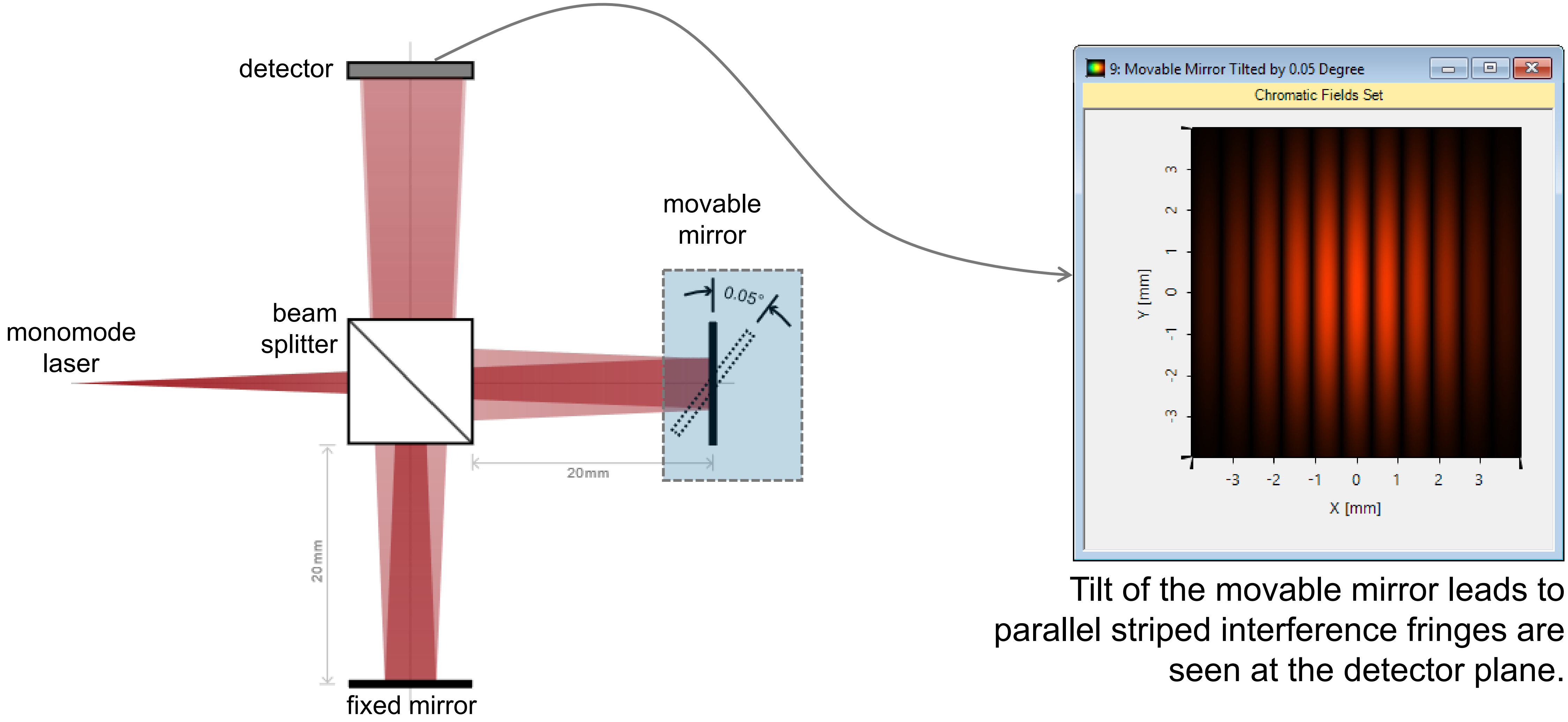
Coherent superposition of two fields reflected from planar mirrors at equivalent-path positions gives no interference fringes.

Result with Shifted Movable Mirror



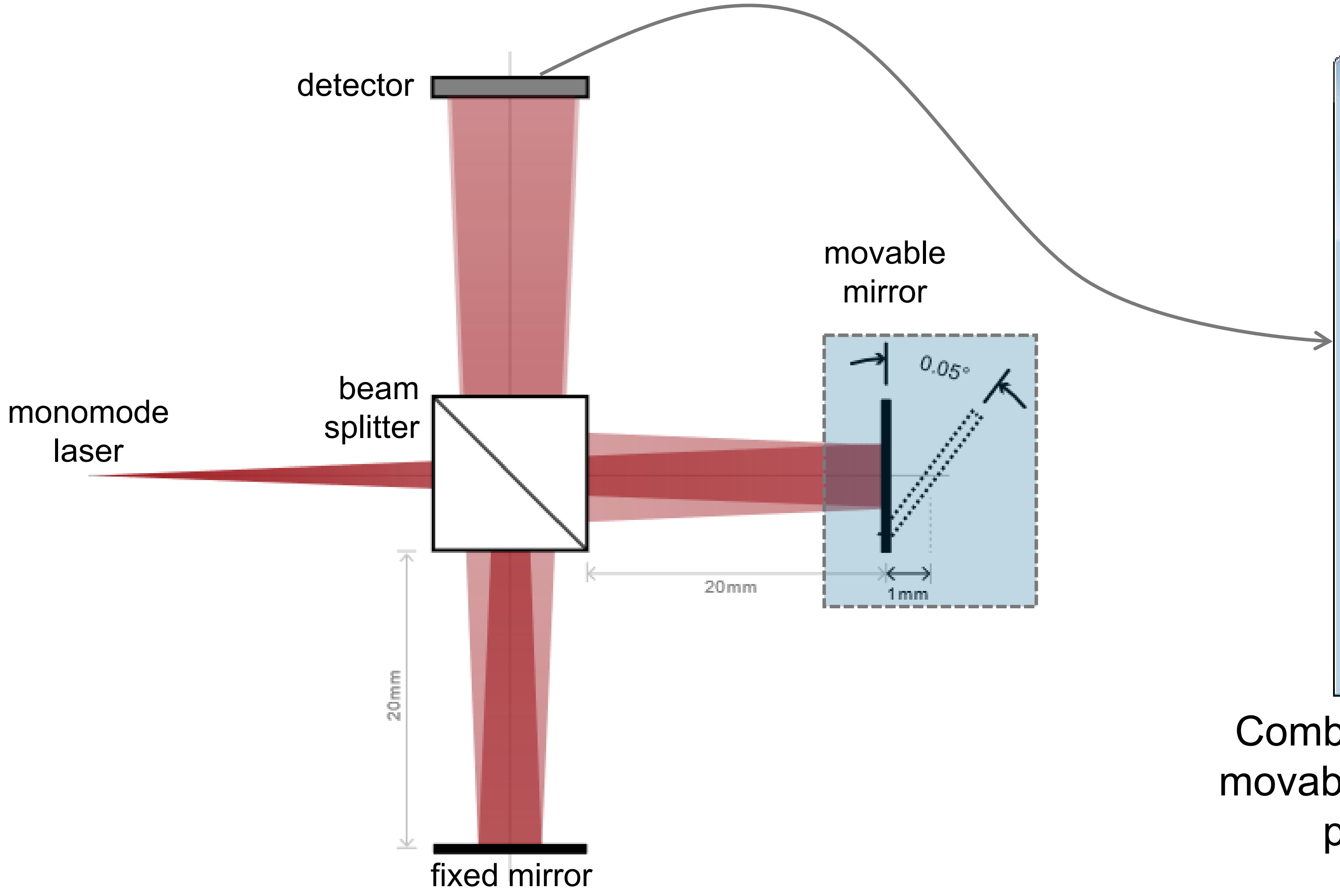
Shift of the movable mirror introduces defocus, and therefore ring fringes are observed at the detector plane.

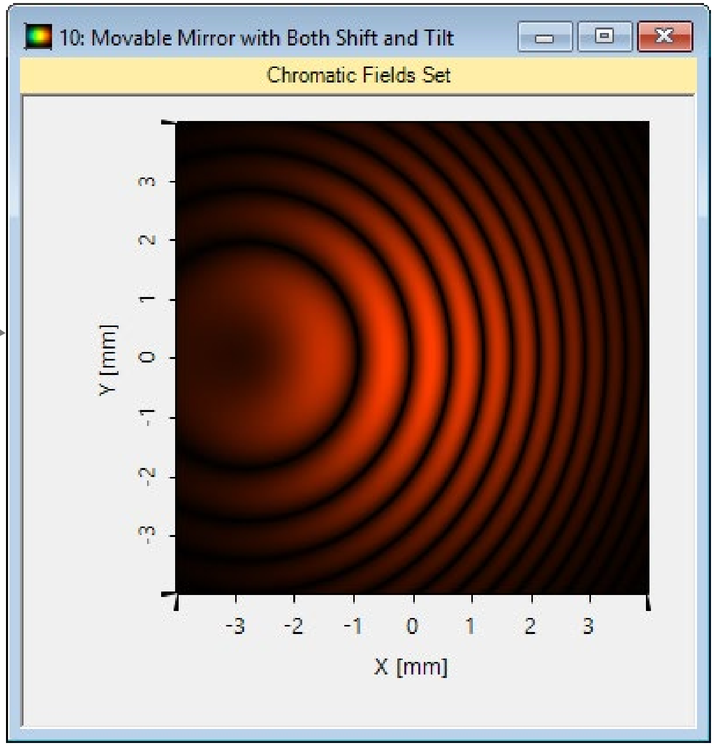
Result with Tilted Movable Mirror



Tilt of the movable mirror leads to parallel striped interference fringes are seen at the detector plane.

Result with Shifted and Tilted Movable Mirror



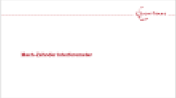


Combination of both shift and tilt of the movable mirror gives rise to shifted ring pattern in the interference fringes.

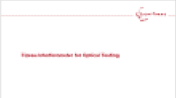
Modeling and Design Examples in VirtualLab Fusion

- Michelson interferometer

- Mach-Zehnder interferometer

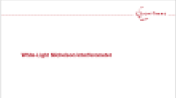


- Fizeau interferometer

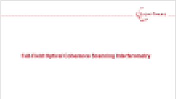


- Coherence measurement

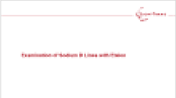
- White light interferometry



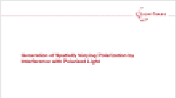
- Coherence scanning interferometry



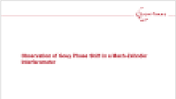
- Spectroscopy with Etalon



- Locally polarized fields by interference

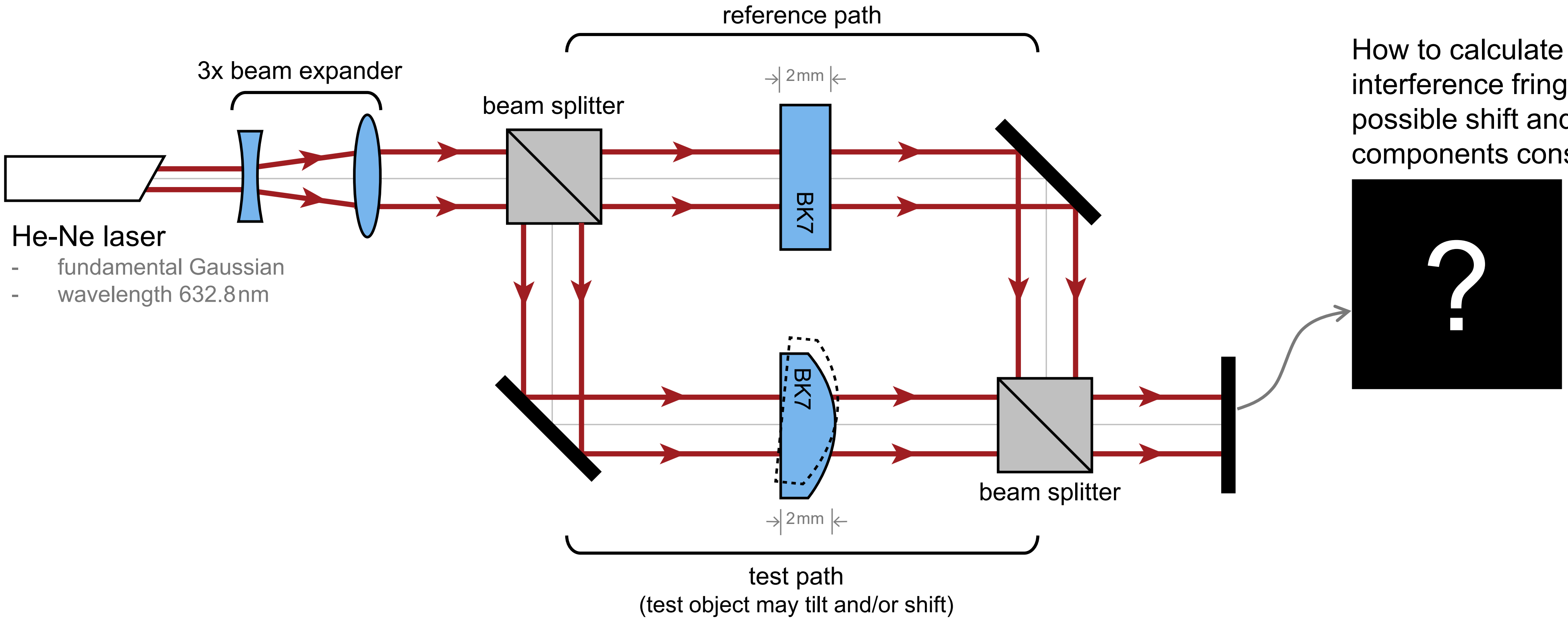


- Gouy phase shift demonstration



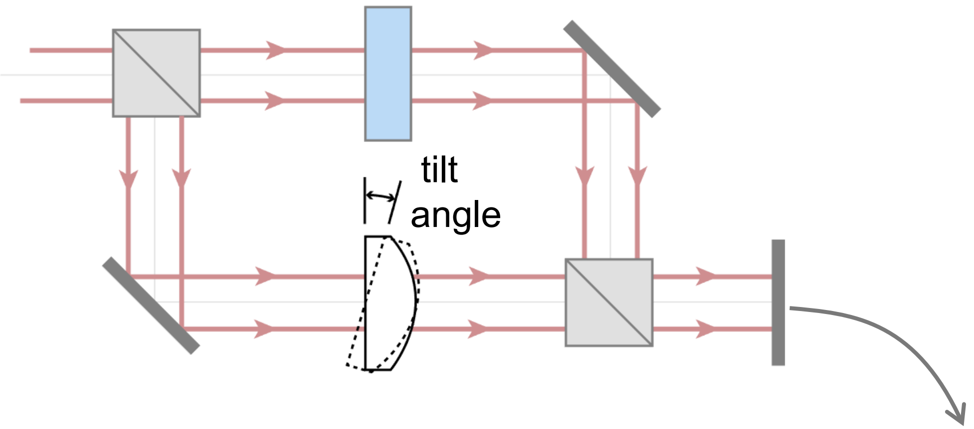
Mach-Zehnder Interferometer

Modeling Task

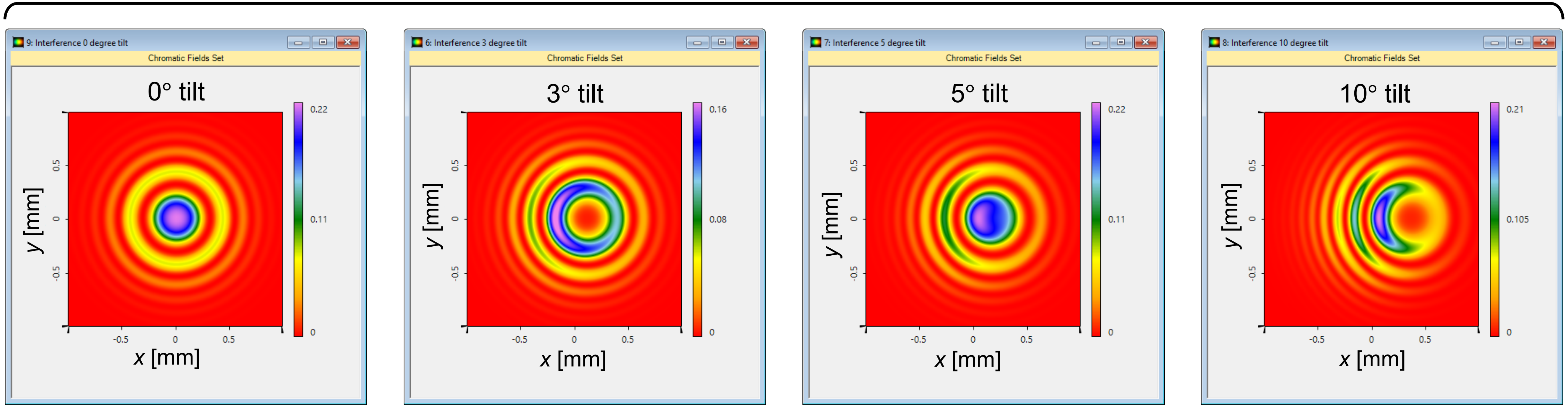


How to calculate interference fringe with the possible shift and tilt of components considered?

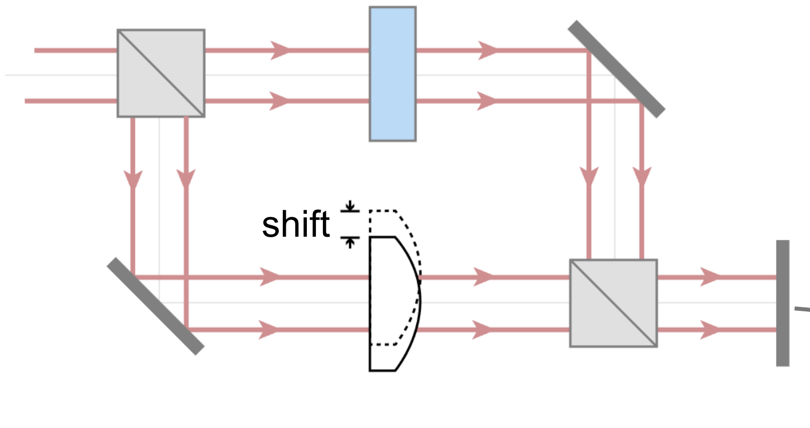
Interference Fringe Due to Component Tilt



Calculation of interference pattern including element tilt takes less than 2 seconds!



Interference Fringe Due to Component Shift



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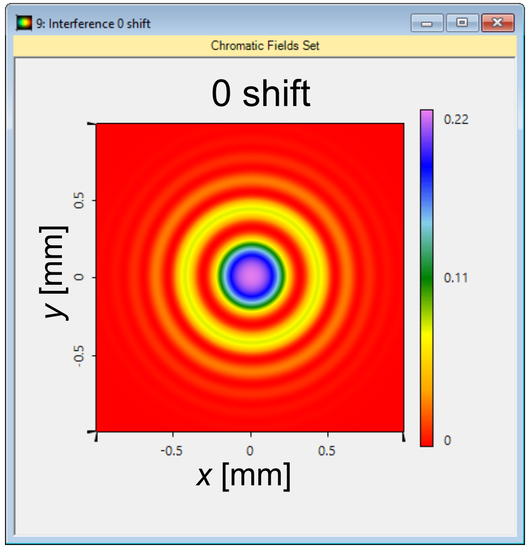

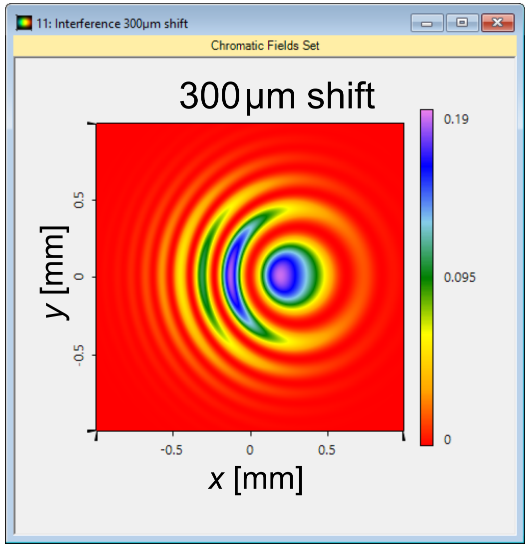

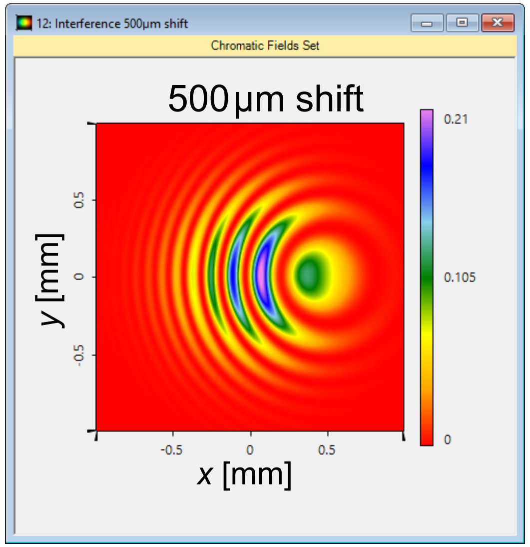

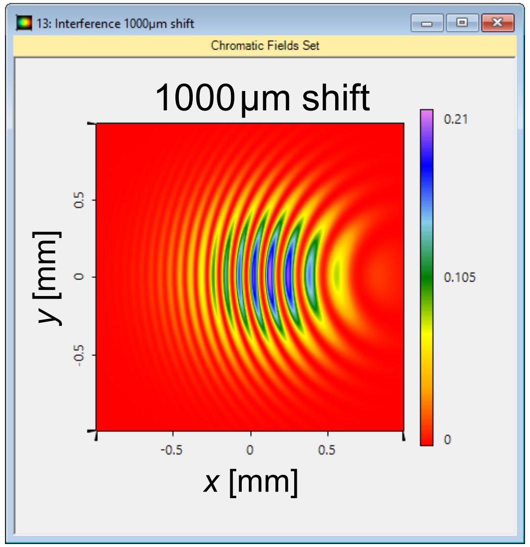

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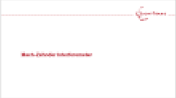
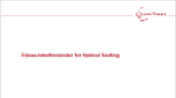
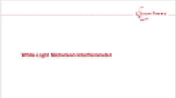
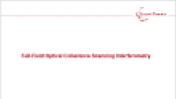
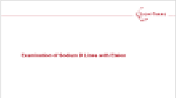
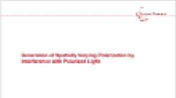
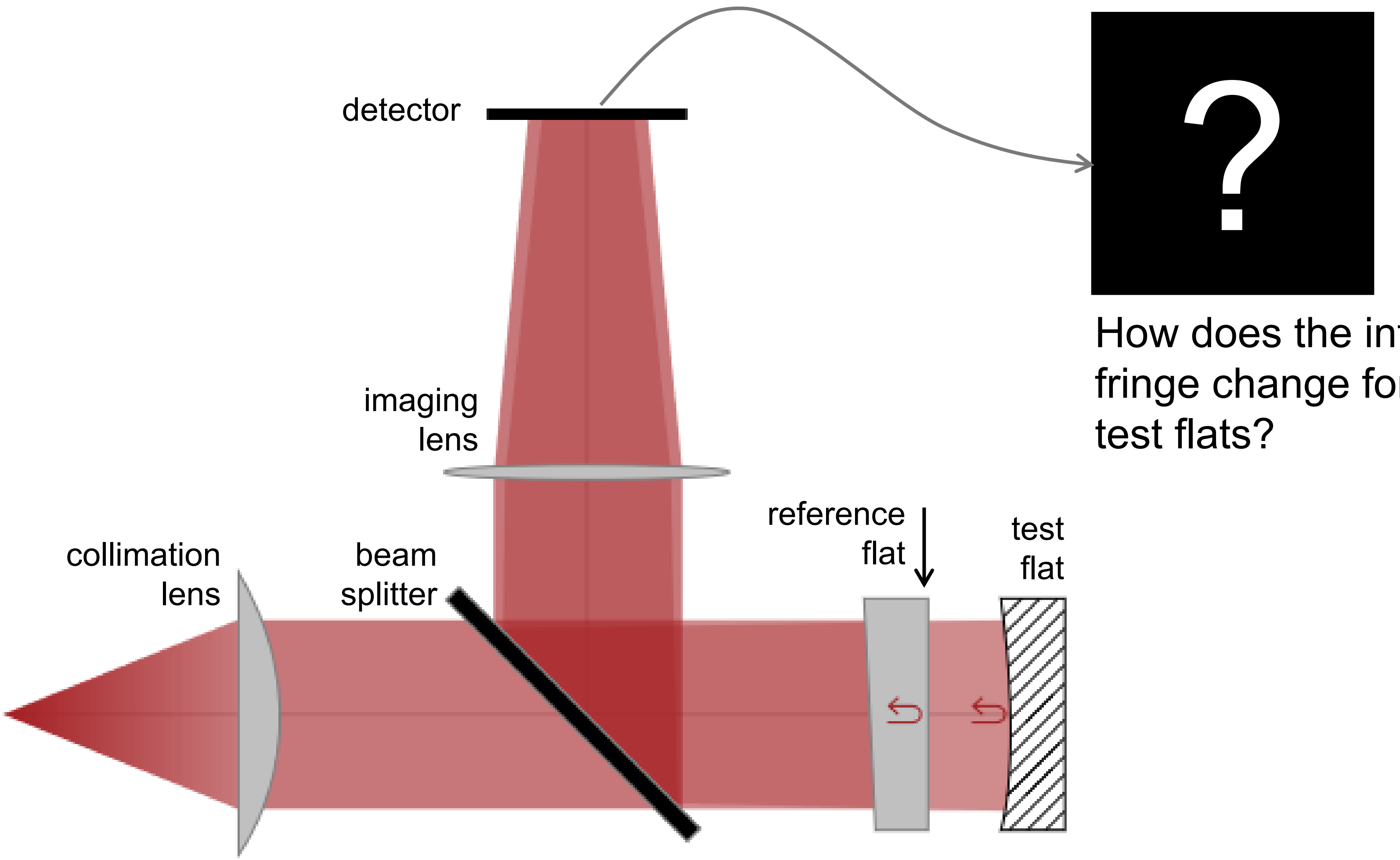




Fizeau Interferometer for Optical Testing

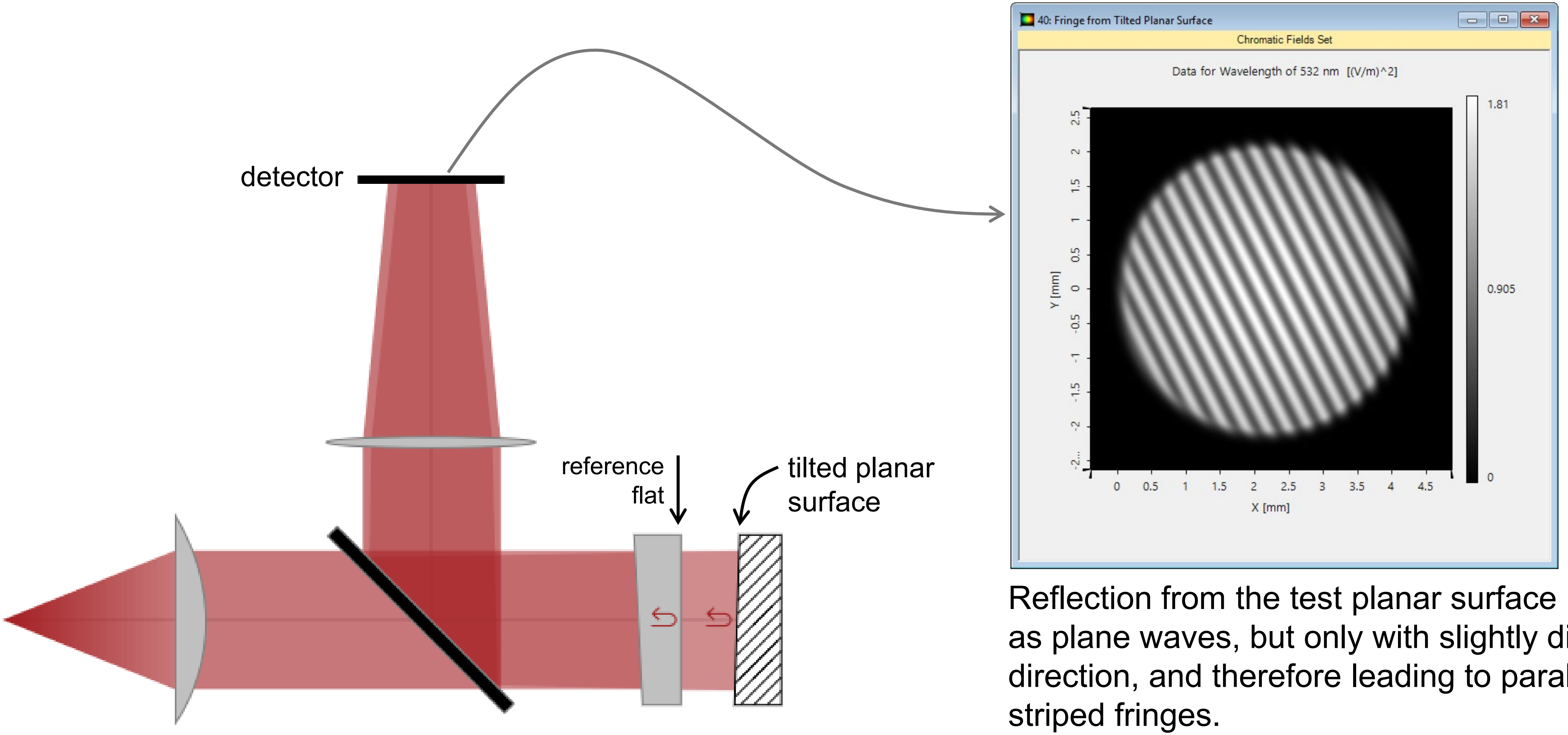
Modeling Task



spherical wave
- wavelength 532 nm
- half-opening angle 26.6°

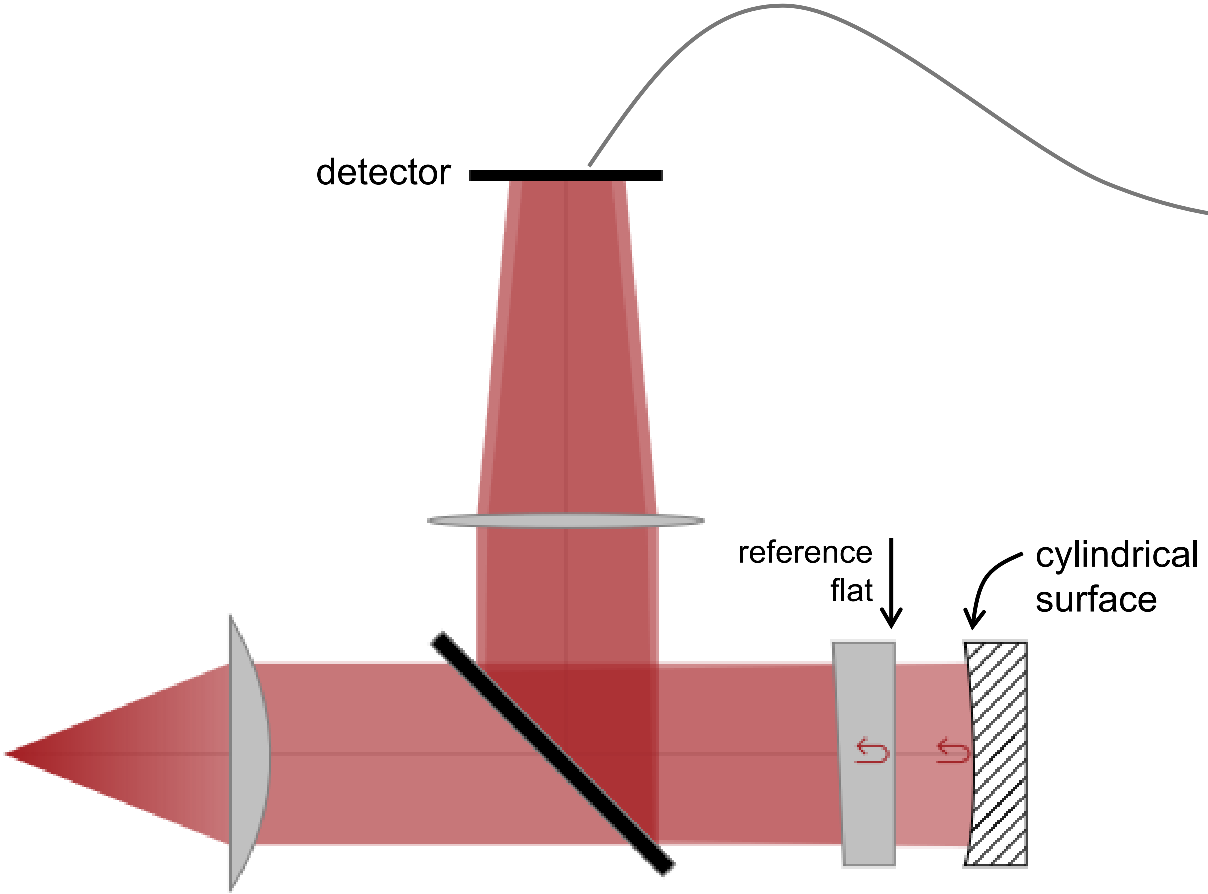
How does the interference fringe change for different test flats?

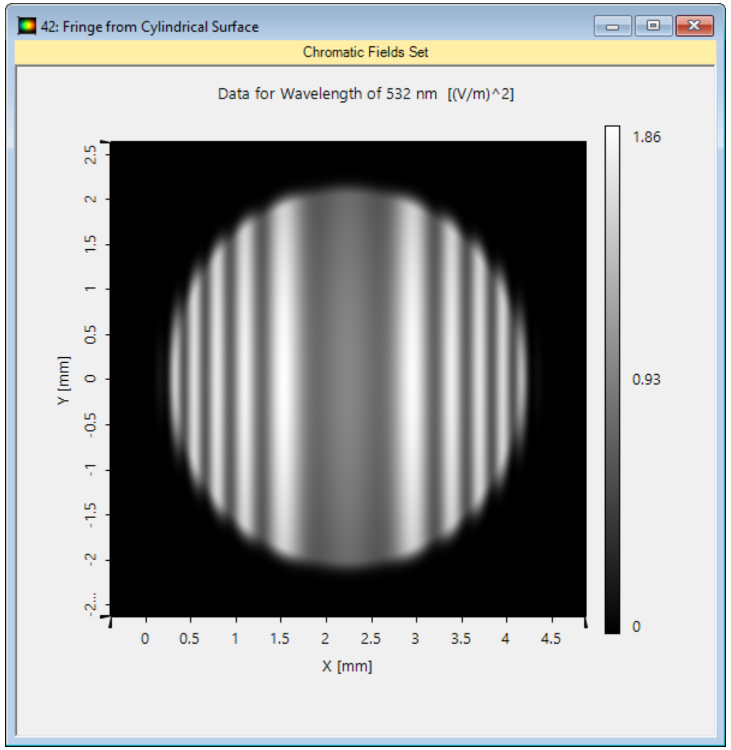
Tilted Planar Surface under Observation



Reflection from the test planar surface remain as plane waves, but only with slightly different direction, and therefore leading to parallel striped fringes.

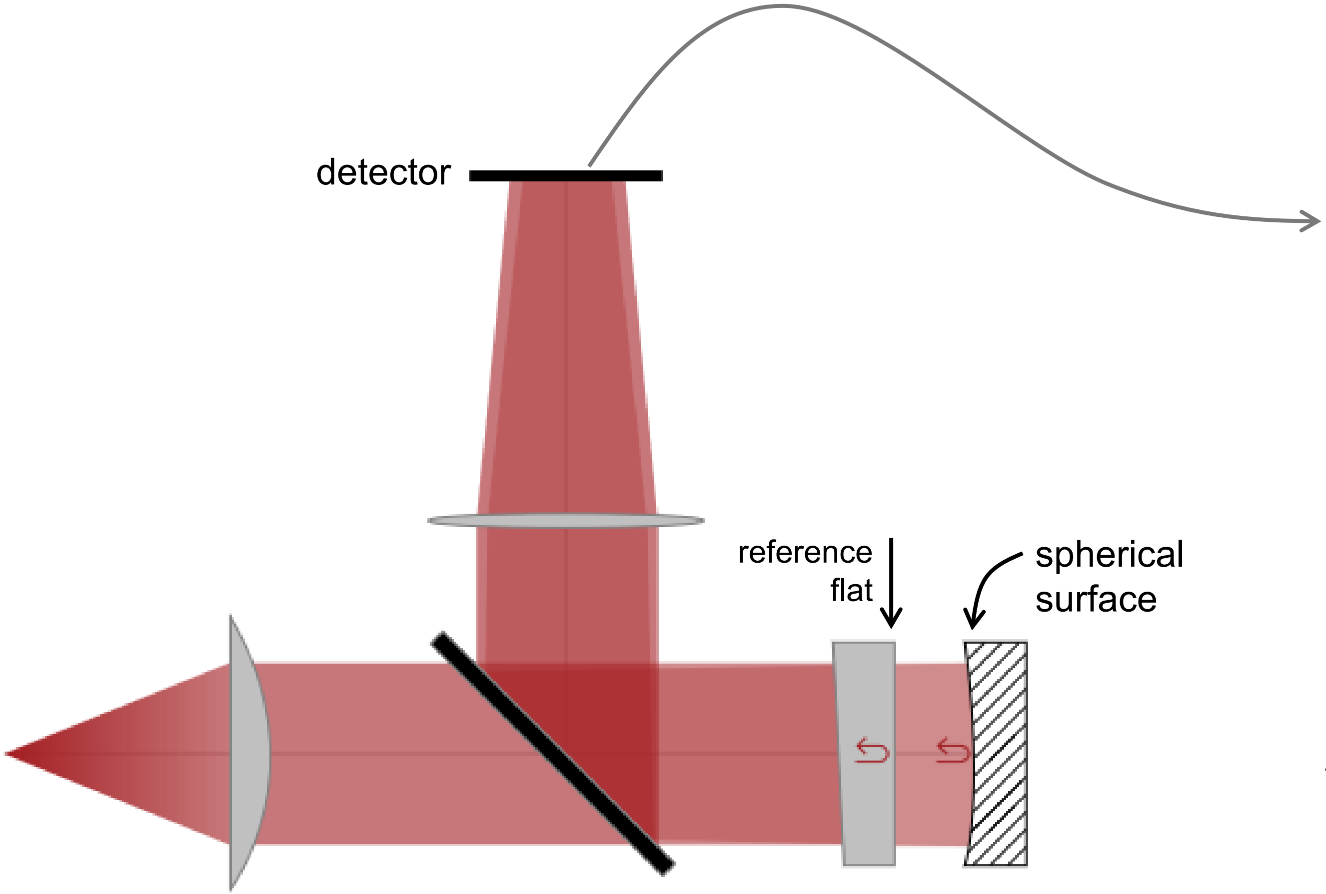
Cylindrical Surface under Observation

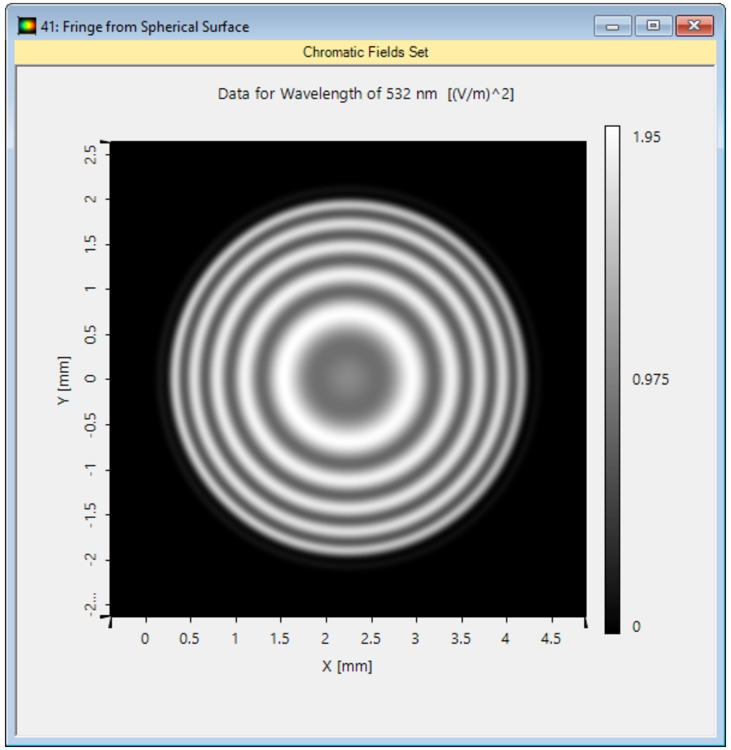




Reflected wavefront from the test cylindrical surface gets curved in one direction, therefore leading to parallel striped fringes but with varying pitch.

Spherical Surface under Observation

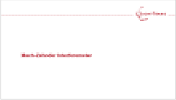


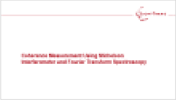
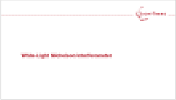
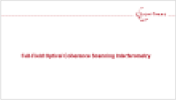


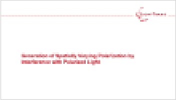
Spherical surface changes the reflected wavefront in radial direction, thus the interference fringes appears as concentric rings.

Modeling and Design Examples in VirtualLab Fusion

- Michelson interferometer
- Mach-Zehnder interferometer
- Fizeau interferometer
- Coherence measurement
- White light interferometry
- Coherence scanning interferometry
- Spectroscopy with Etalon
- Locally polarized fields by interference
- Gouy phase shift demonstration

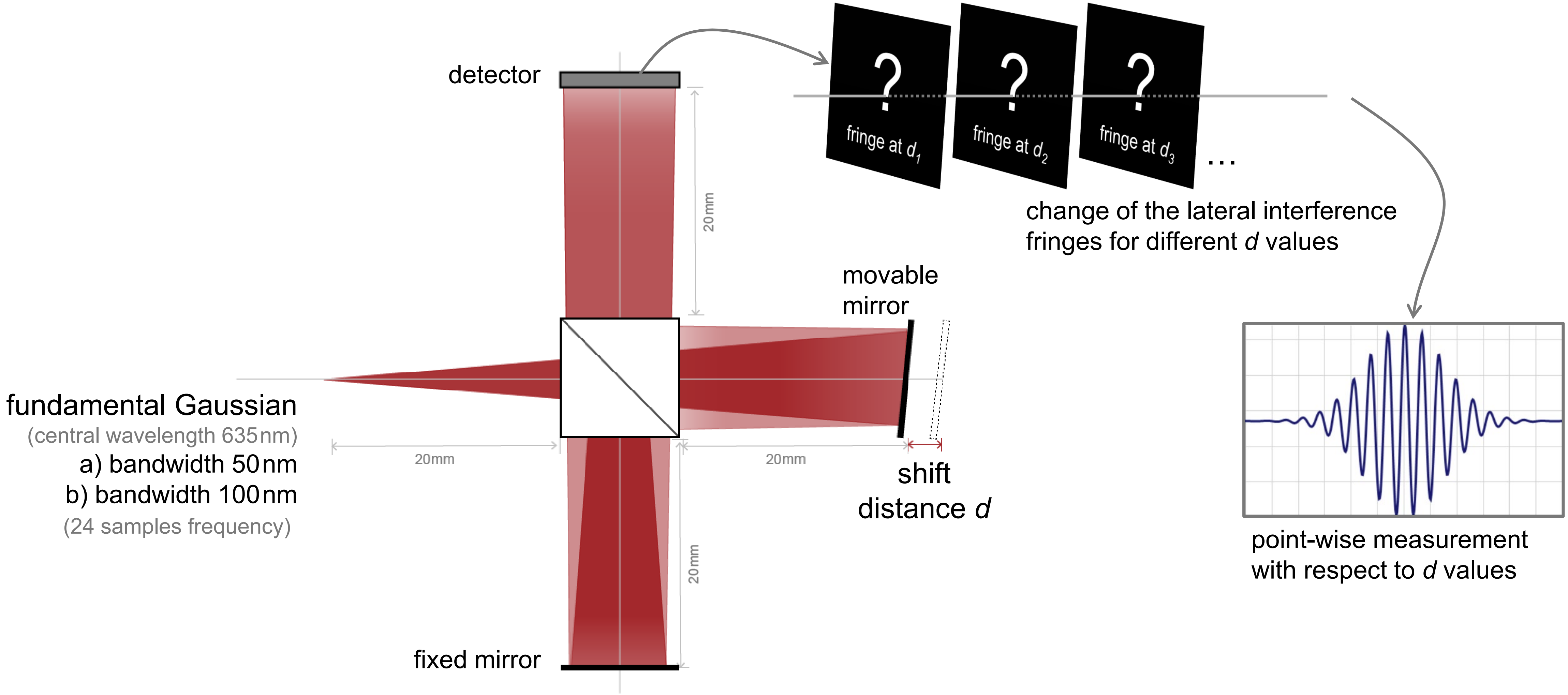



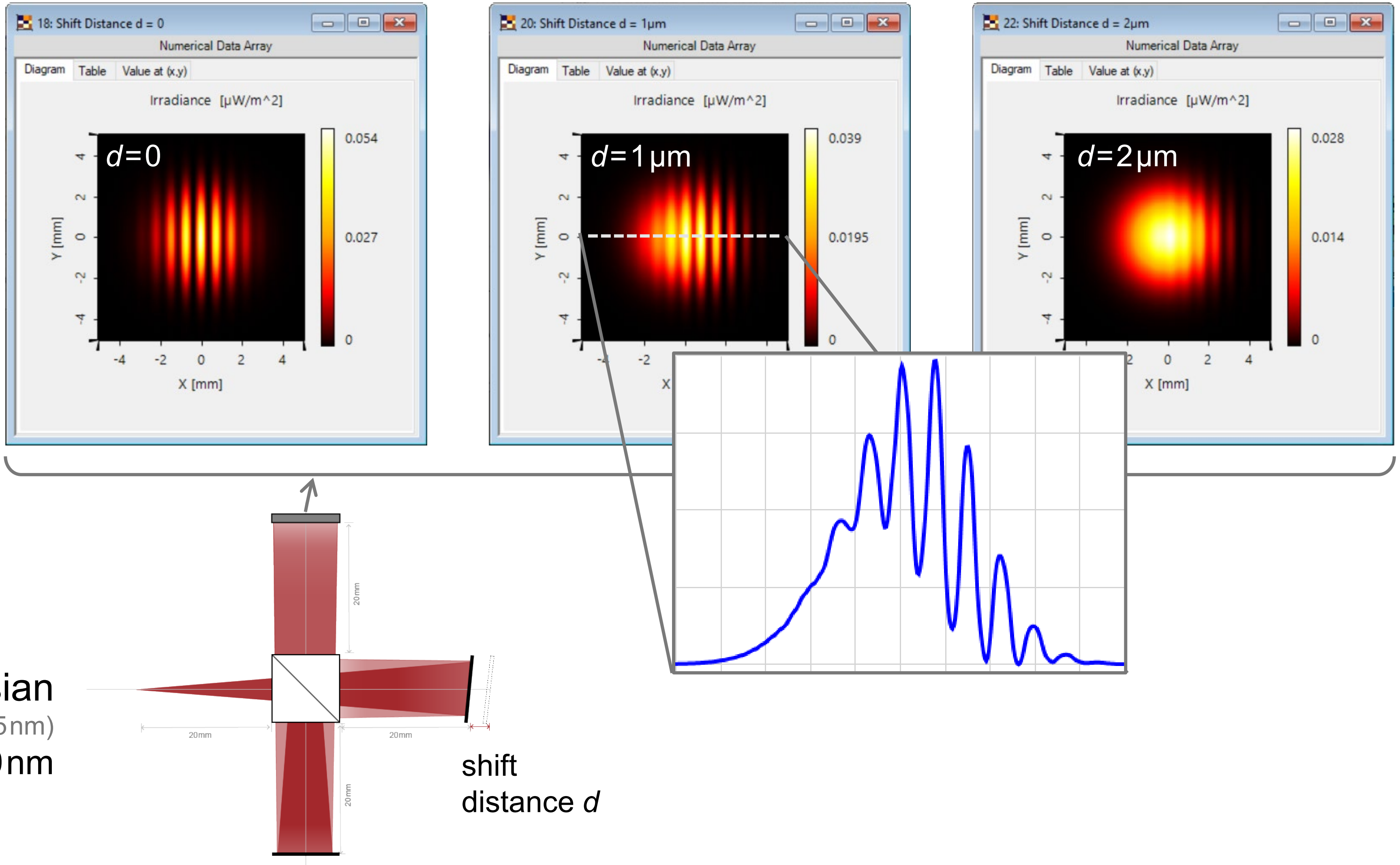



Coherence Measurement Using Michelson Interferometer and Fourier Transform Spectroscopy

Modeling Task



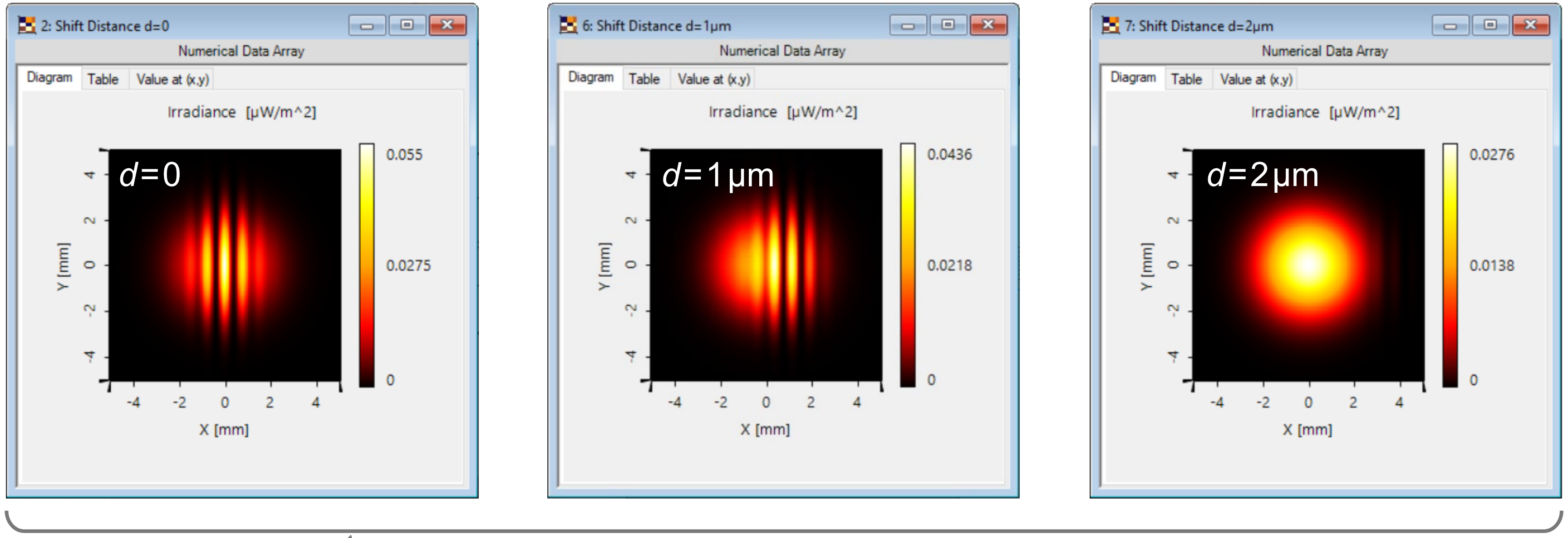
Lateral Interference Fringes – 50 nm Bandwidth



fundamental Gaussian
(central wavelength 635 nm)
a) bandwidth 50 nm

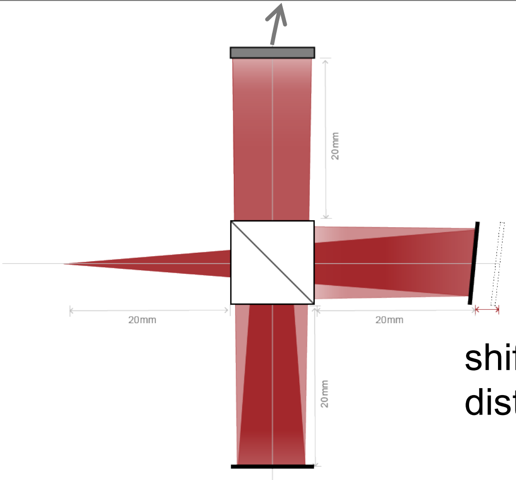
shift
distance *d*

Lateral Interference Fringes – 100 nm Bandwidth



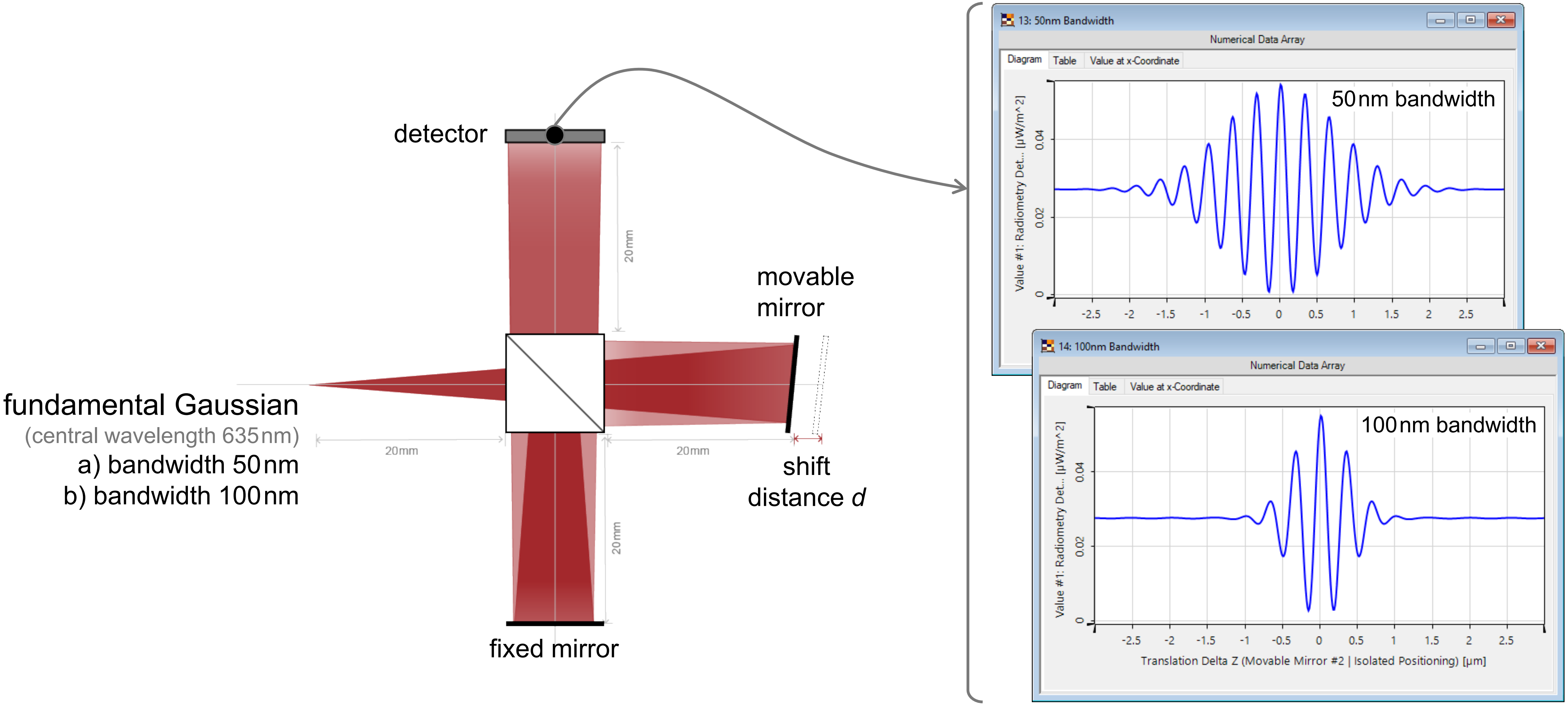
Broader spectral bandwidth leads to shorter coherent length; and therefore the interference fringe starts to vanish sooner in comparison to the case with narrower bandwidth.

fundamental Gaussian
(central wavelength 635 nm)
b) bandwidth: 100 nm



shift distance *d*

Pointwise Measurement

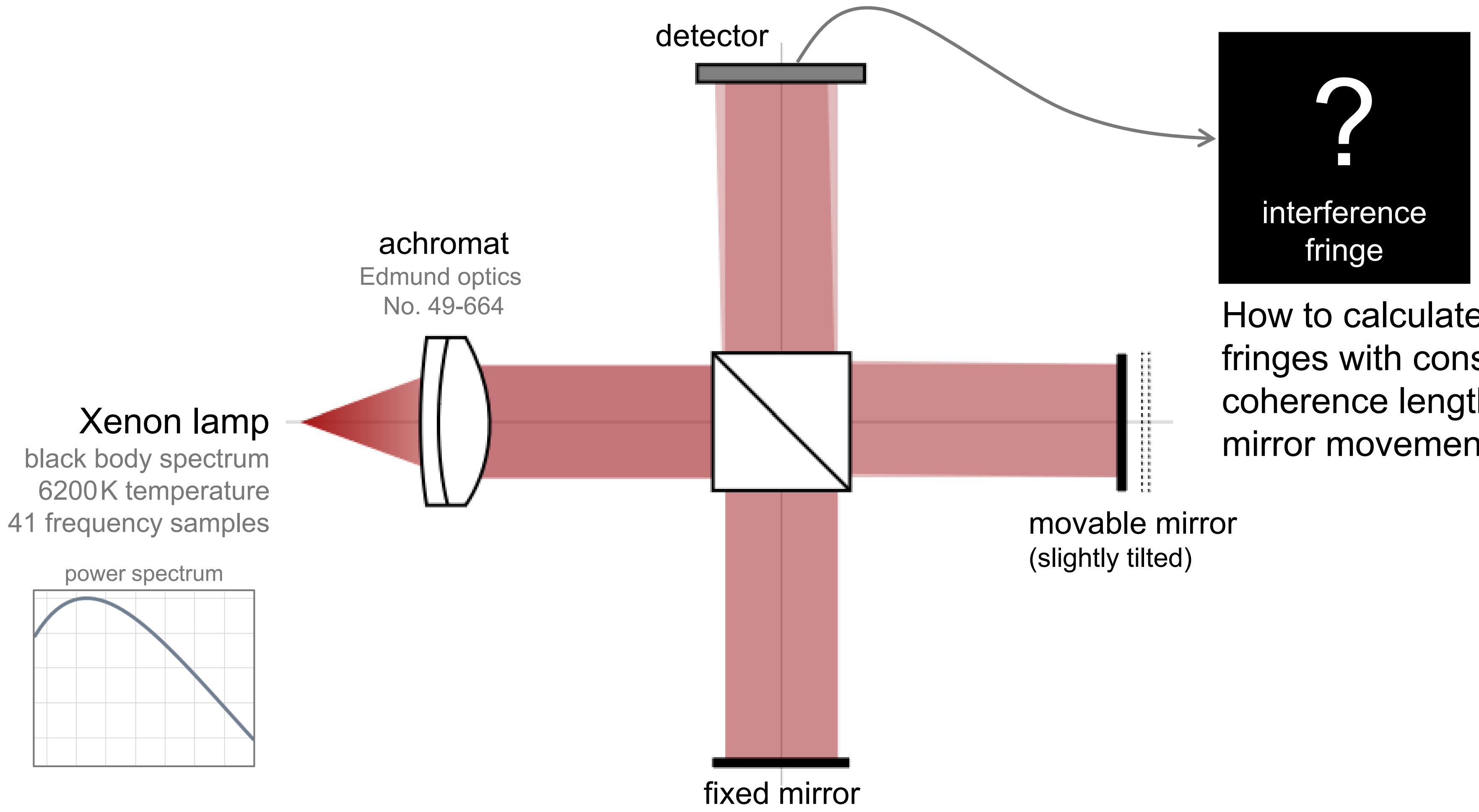


Modeling and Design Examples in VirtualLab Fusion

- Michelson interferometer
- Mach-Zehnder interferometer
- Fizeau interferometer
- Coherence measurement
- White light interferometry
- Coherence scanning interferometry
- Spectroscopy with Etalon
- Locally polarized fields by interference
- Gouy phase shift demonstration

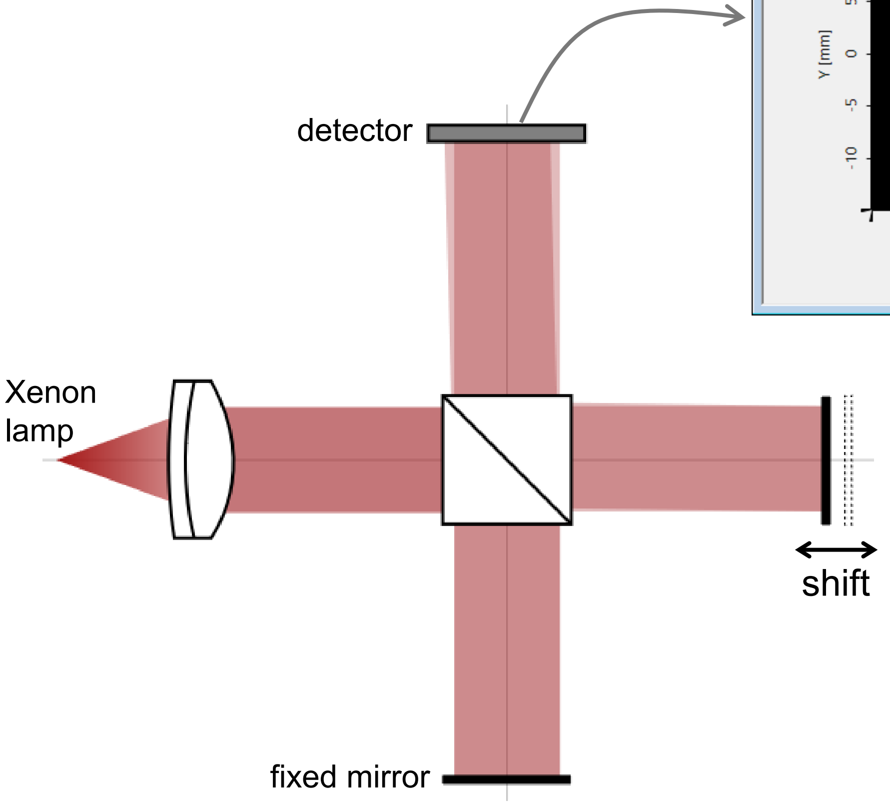
White-Light Michelson Interferometer

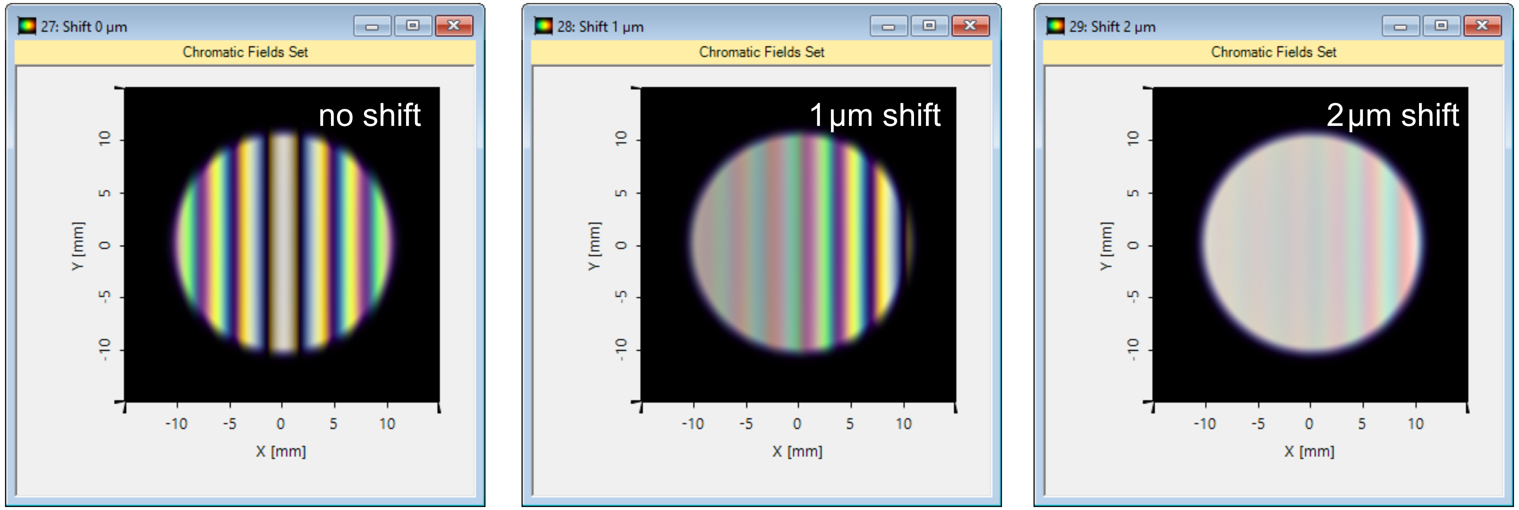
Modeling Task



How to calculate the interference fringes with consideration of the finite coherence length of the source and the mirror movement?

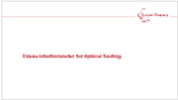
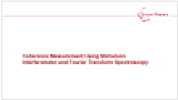
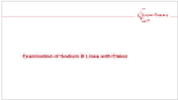
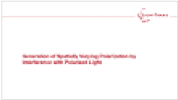
Change in Interference Fringes





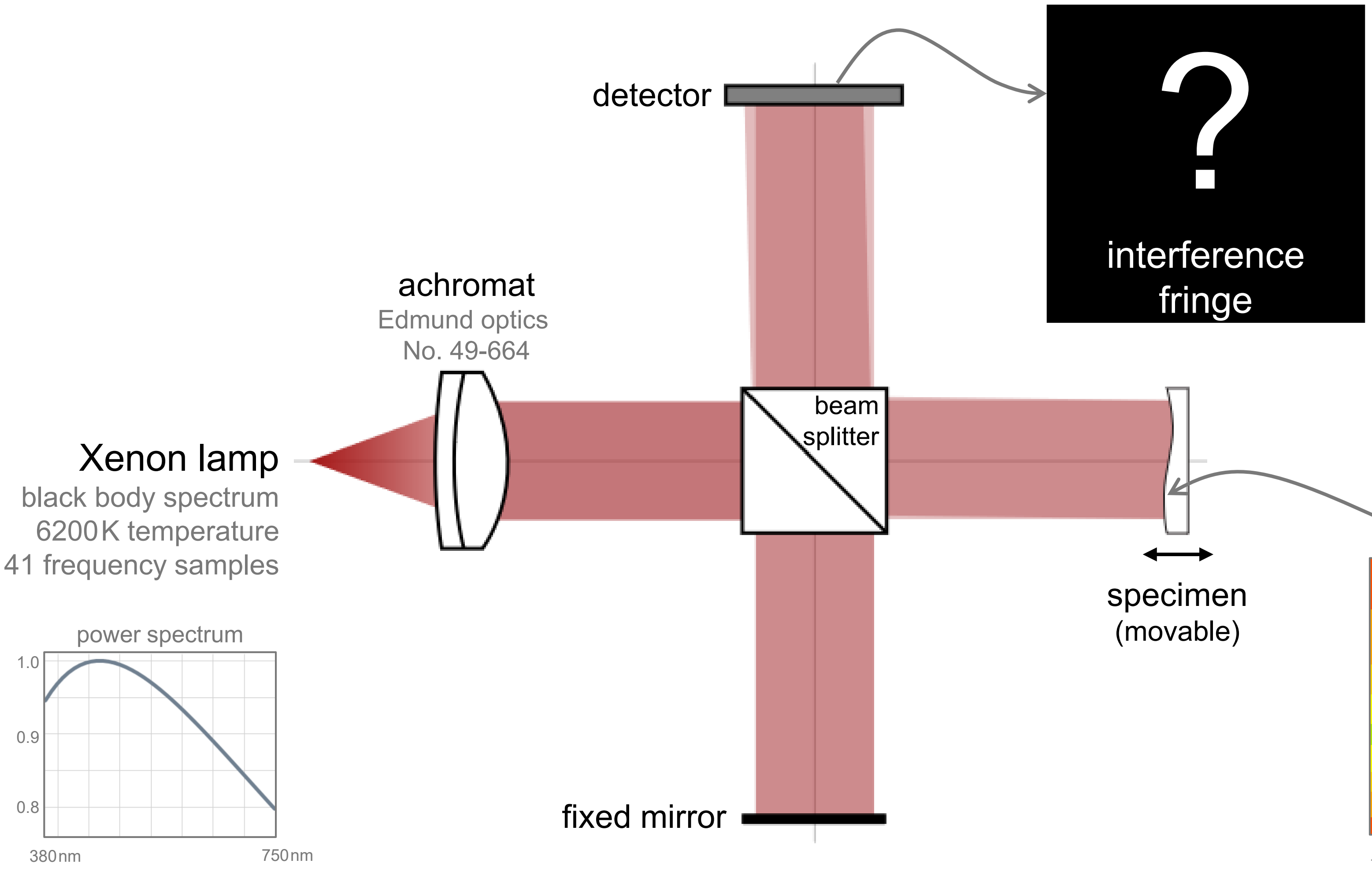
When the movable mirror moves from 0 µm to 2 µm, the contrast of interference pattern decreases, due to limited coherence length of the light source.

Modeling and Design Examples in VirtualLab Fusion

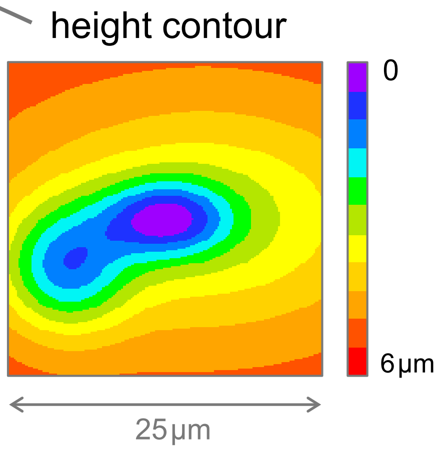
- Michelson interferometer 
- Mach-Zehnder interferometer 
- Fizeau interferometer 
- Coherence measurement 
- White light interferometry 
- Coherence scanning interferometry 
- Spectroscopy with Etalon 
- Locally polarized fields by interference 
- Gouy phase shift demonstration 

Full-Field Optical Coherence Scanning Interferometry

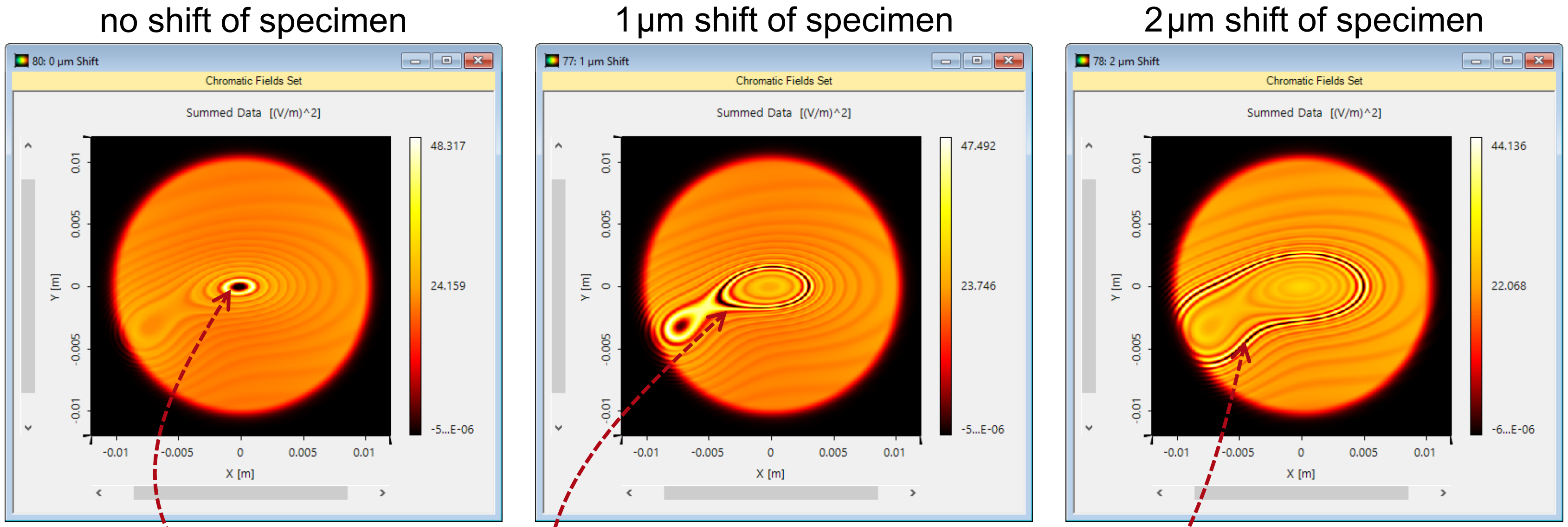
Modeling Task

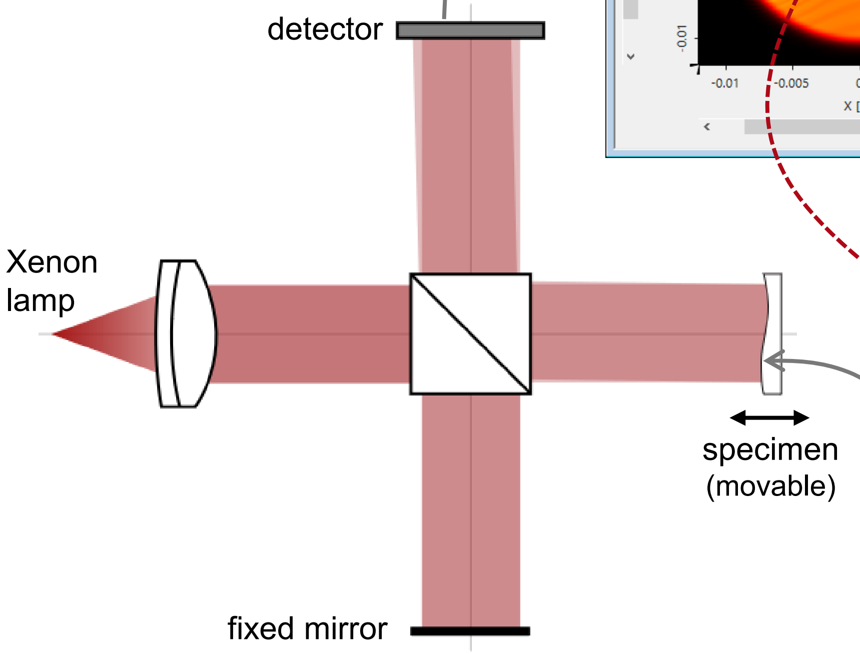


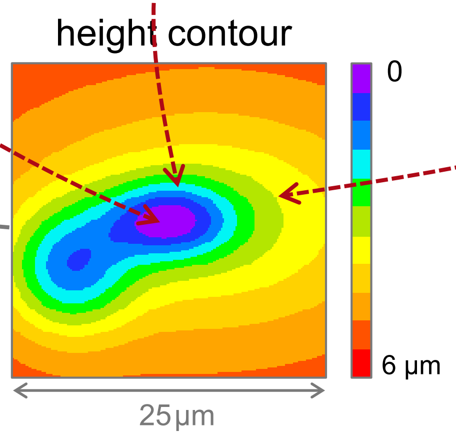
How to calculate the interference pattern and even to derive the height profile of the specimen under test?



Simulated Interference Fringes





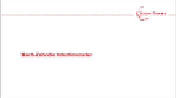


Contour lines of interference fringes corresponds to the height contour of the specimen under measurement.

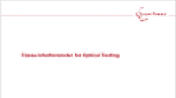
Modeling and Design Examples in VirtualLab Fusion

- Michelson interferometer

- Mach-Zehnder interferometer

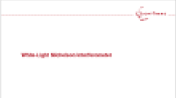


- Fizeau interferometer

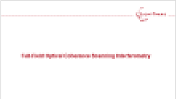


- Coherence measurement

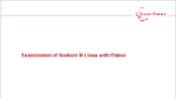
- White light interferometry



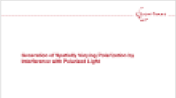
- Coherence scanning interferometry



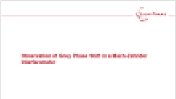
- Spectroscopy with Etalon



- Locally polarized fields by interference

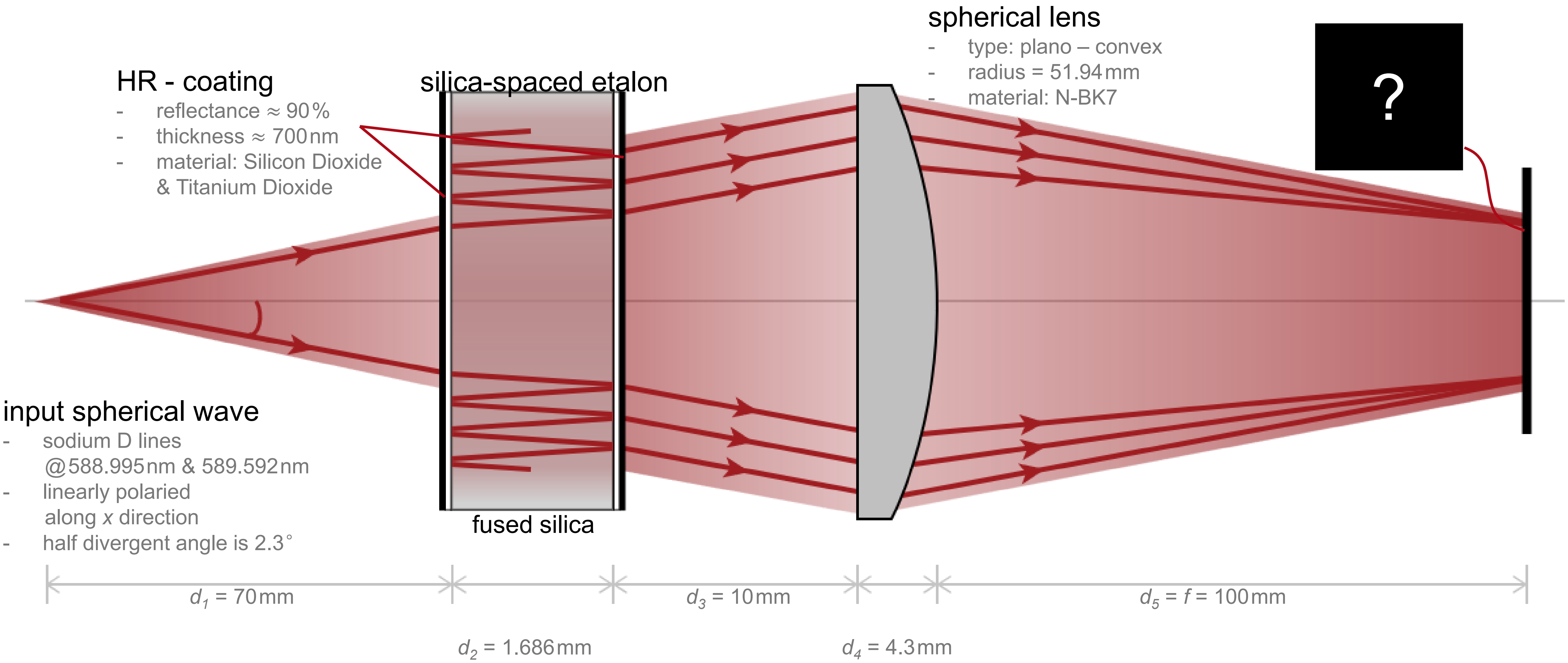


- Gouy phase shift demonstration

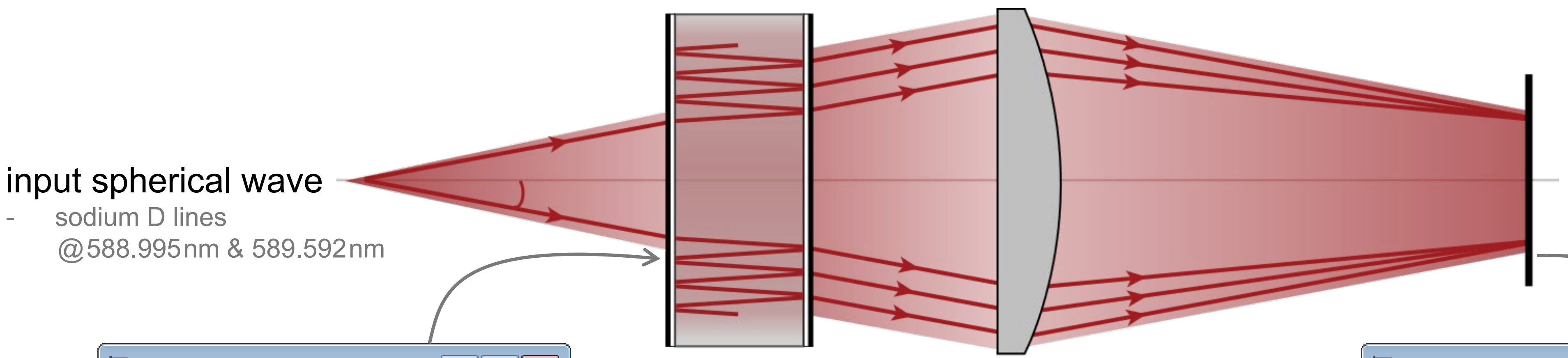


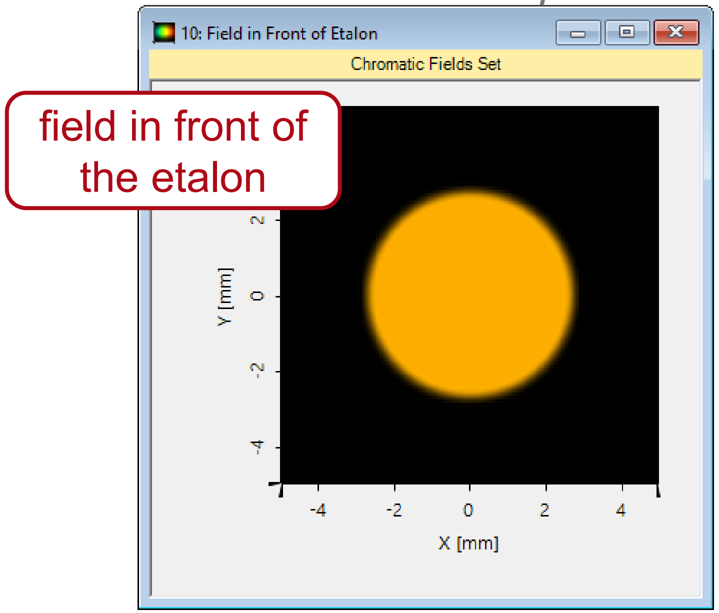
Examination of Sodium D Lines with Etalon

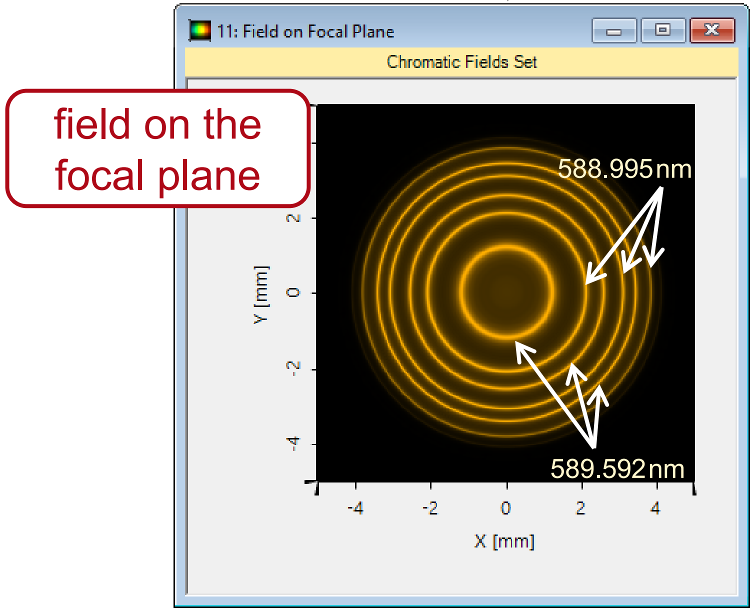
Modeling Task



Visualization of Both Spectrum Lines



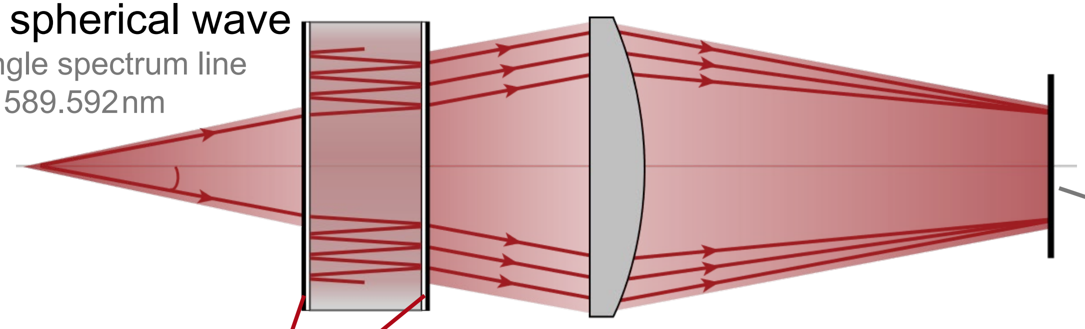




Finesse vs. Coating Reflectance

input spherical wave

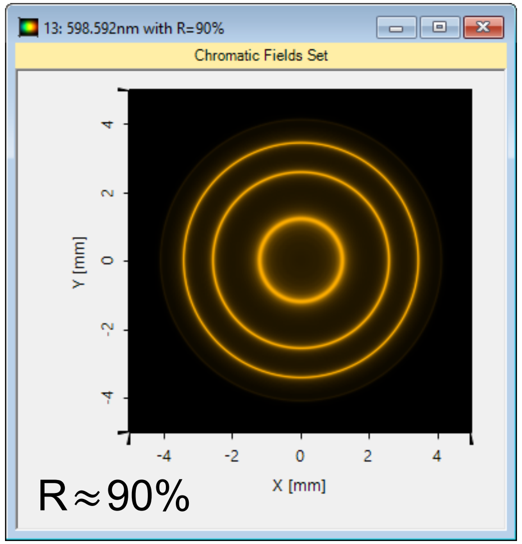
- single spectrum line @589.592nm

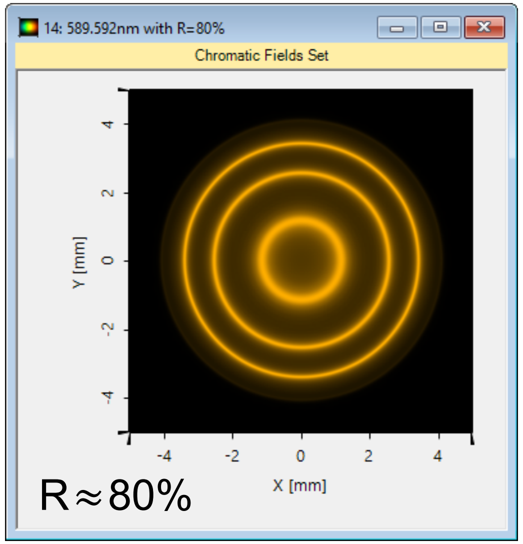


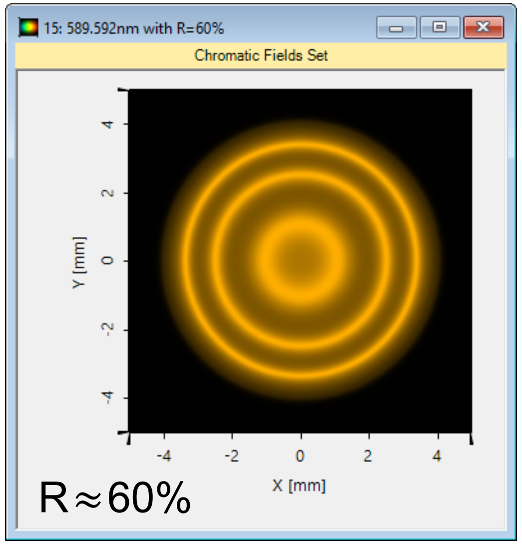
HR - coating

- reflectance ≈90%, 80%, 60%

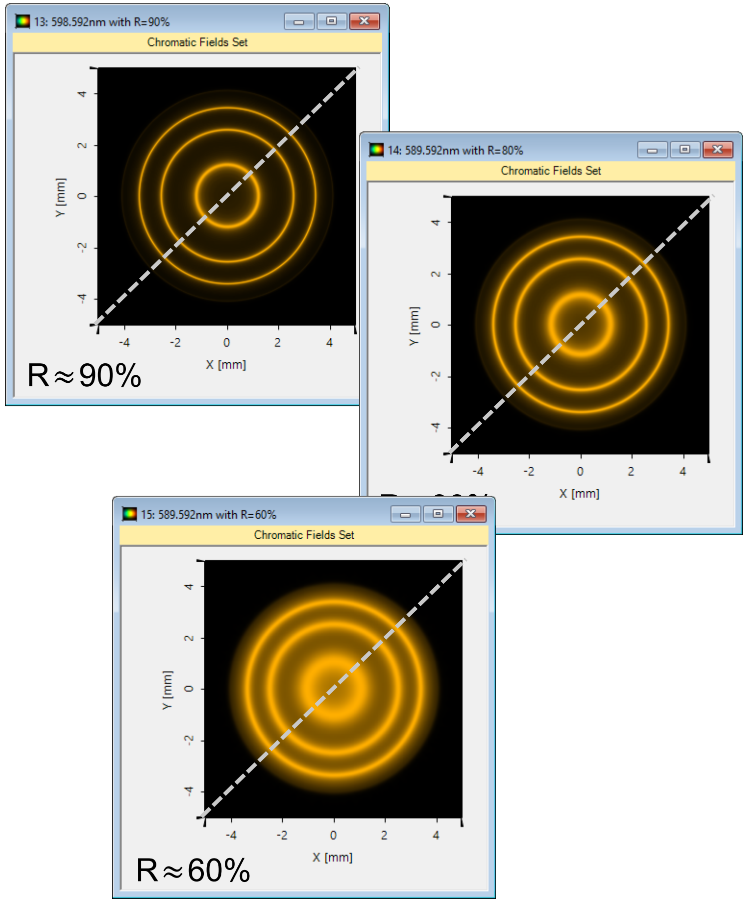
Sharpness of the interference fringes depends on the reflectance of the coatings on the etalon.



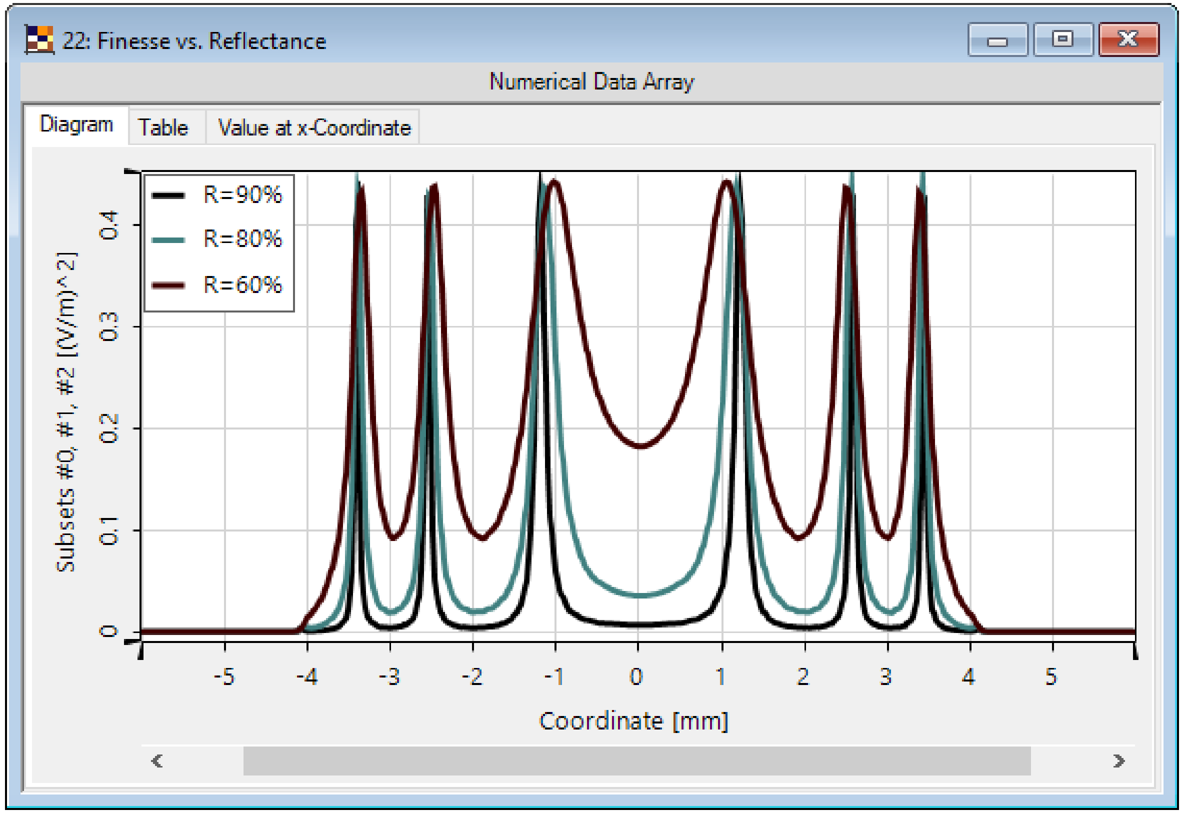




Finesse vs. Coating Reflectance

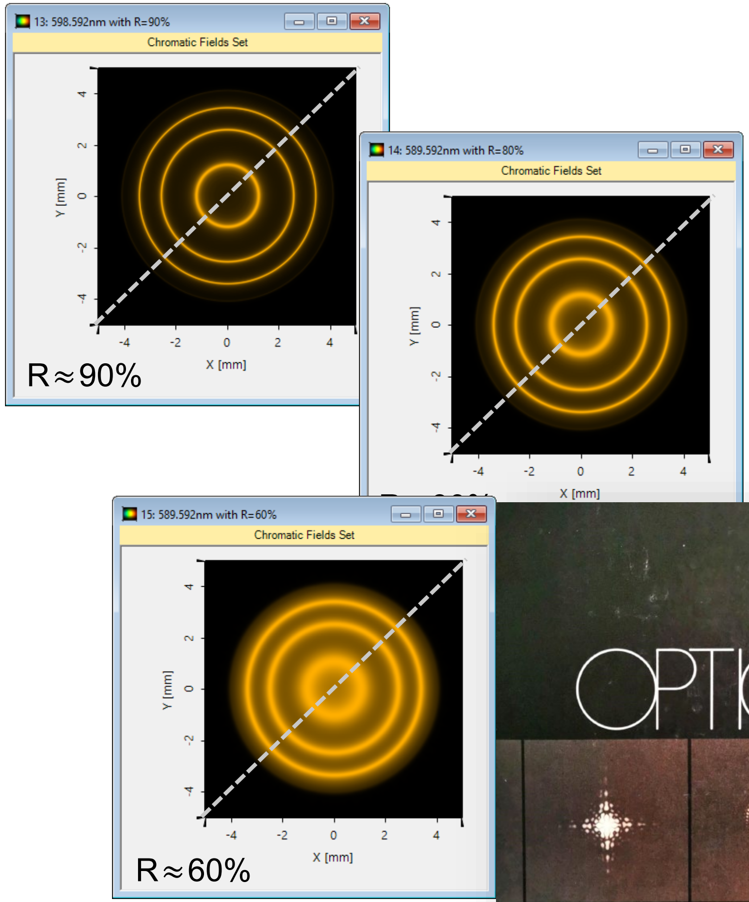


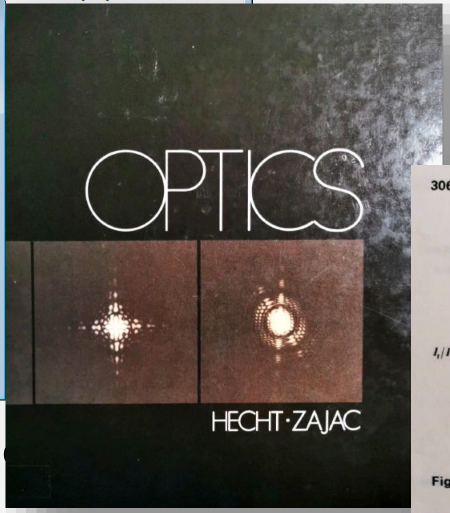
the higher reflectance, the higher finesse

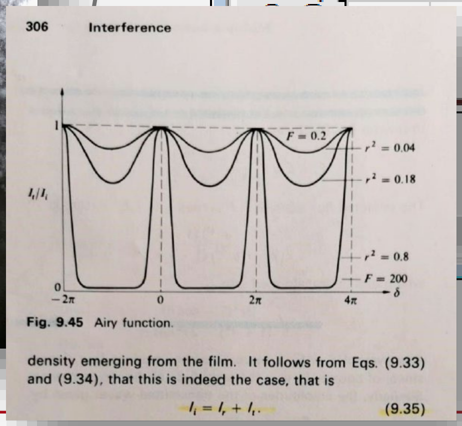


extracting 1D data along the diagonal direction

Finesse vs. Coating Reflectance







306 Interference

I_t/I_i

$F = 0.2$

$r^2 = 0.04$

$r^2 = 0.18$

$r^2 = 0.8$

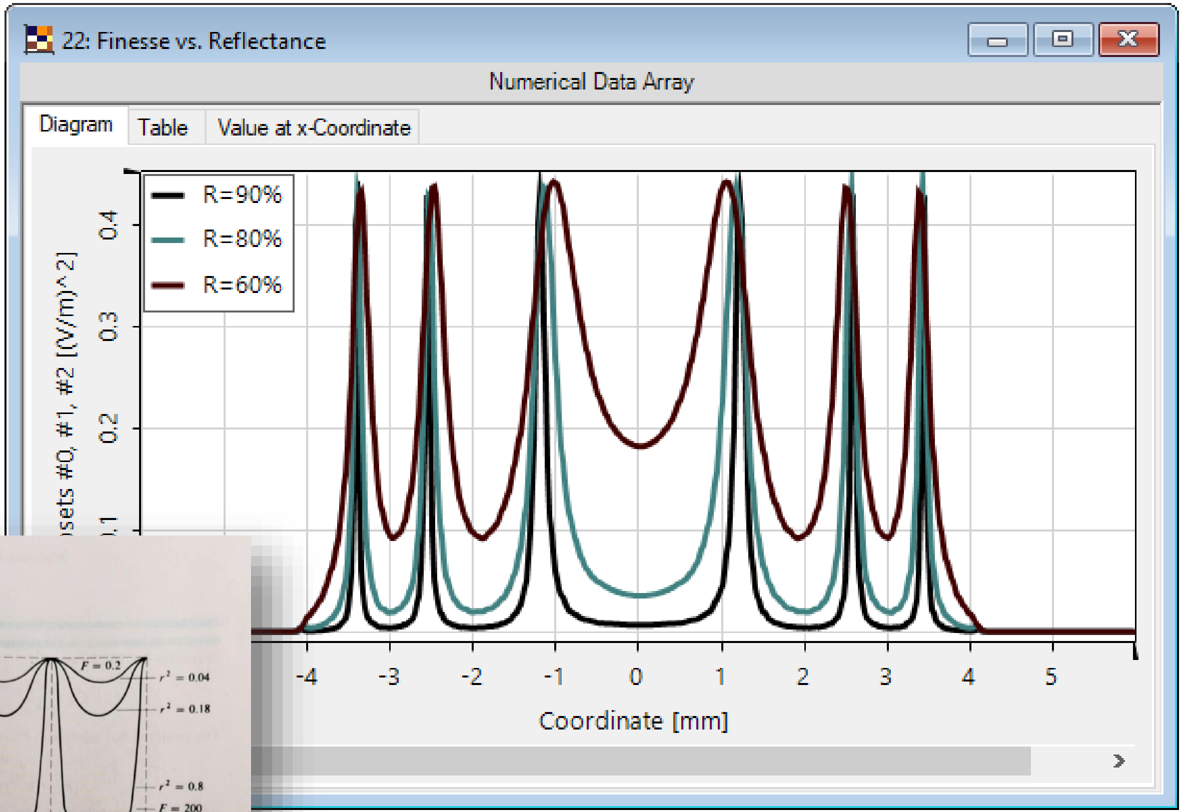
$F = 200$

Fig. 9.45 Airy function.

density emerging from the film. It follows from Eqs. (9.33) and (9.34), that this is indeed the case, that is

$$I_i = I_r + I_t. \quad (9.35)$$

the higher reflectance, the higher finesse



extracting 1D data along th

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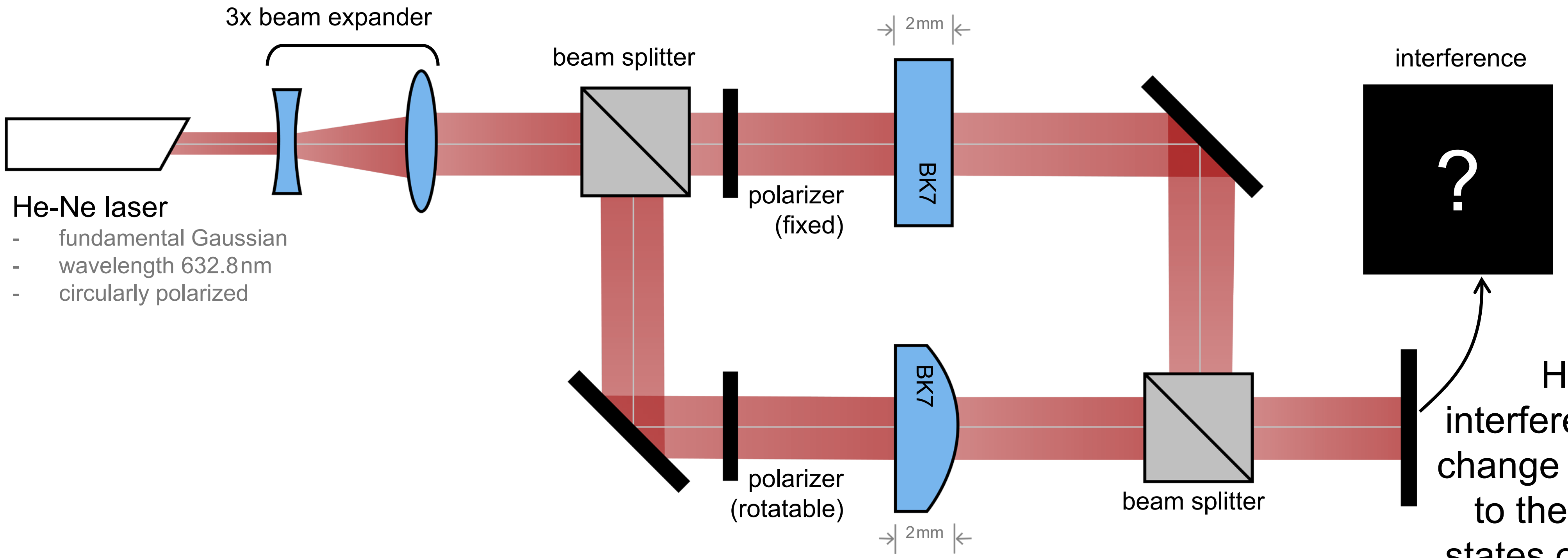
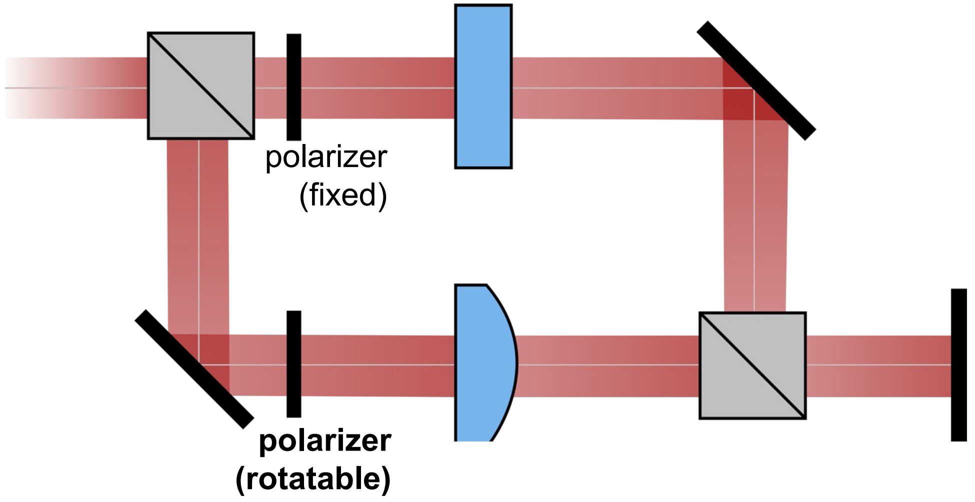
Generation of Spatially Varying Polarization by Interference with Polarized Light

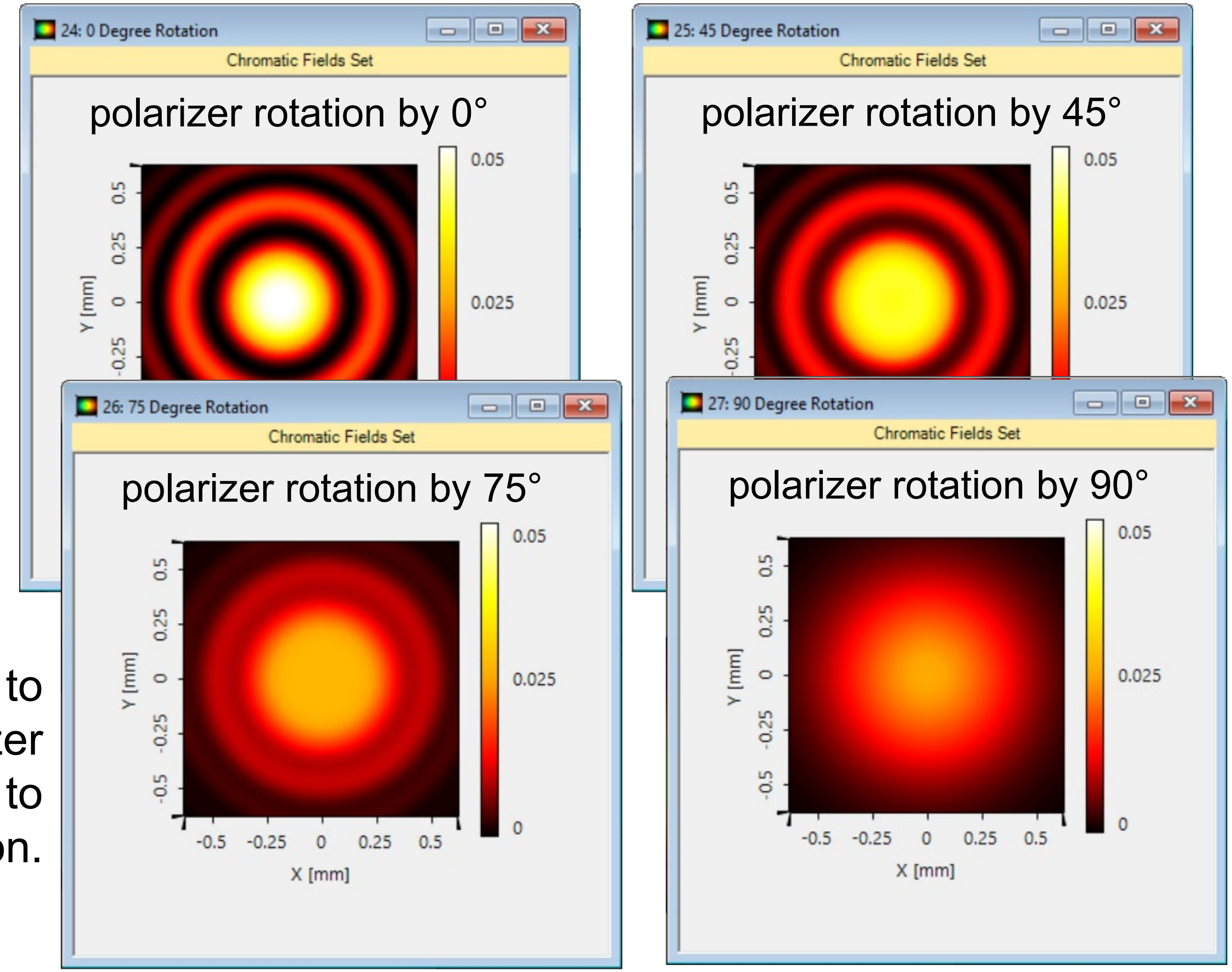
Modeling Task



How does the interference pattern change with respect to the polarization states of two arms?

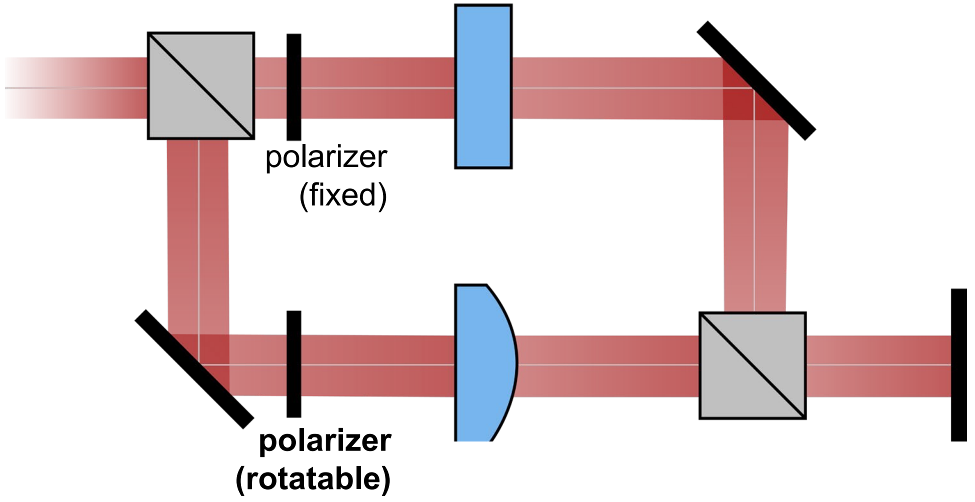
Interference Pattern Changes with Polarizer Rotation

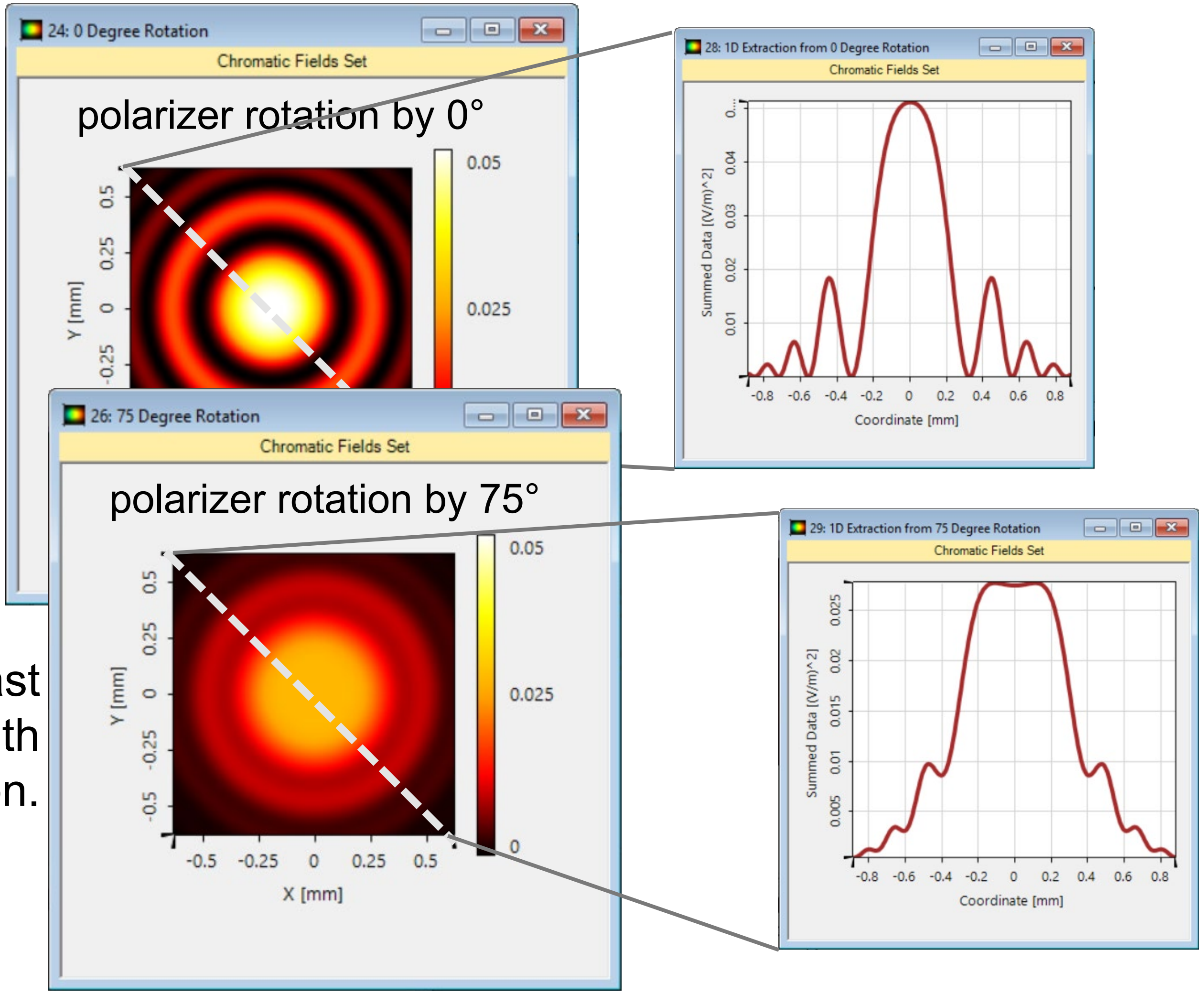




Interference fringes start to disappear, when polarizer rotates from parallel to orthogonal orientation.

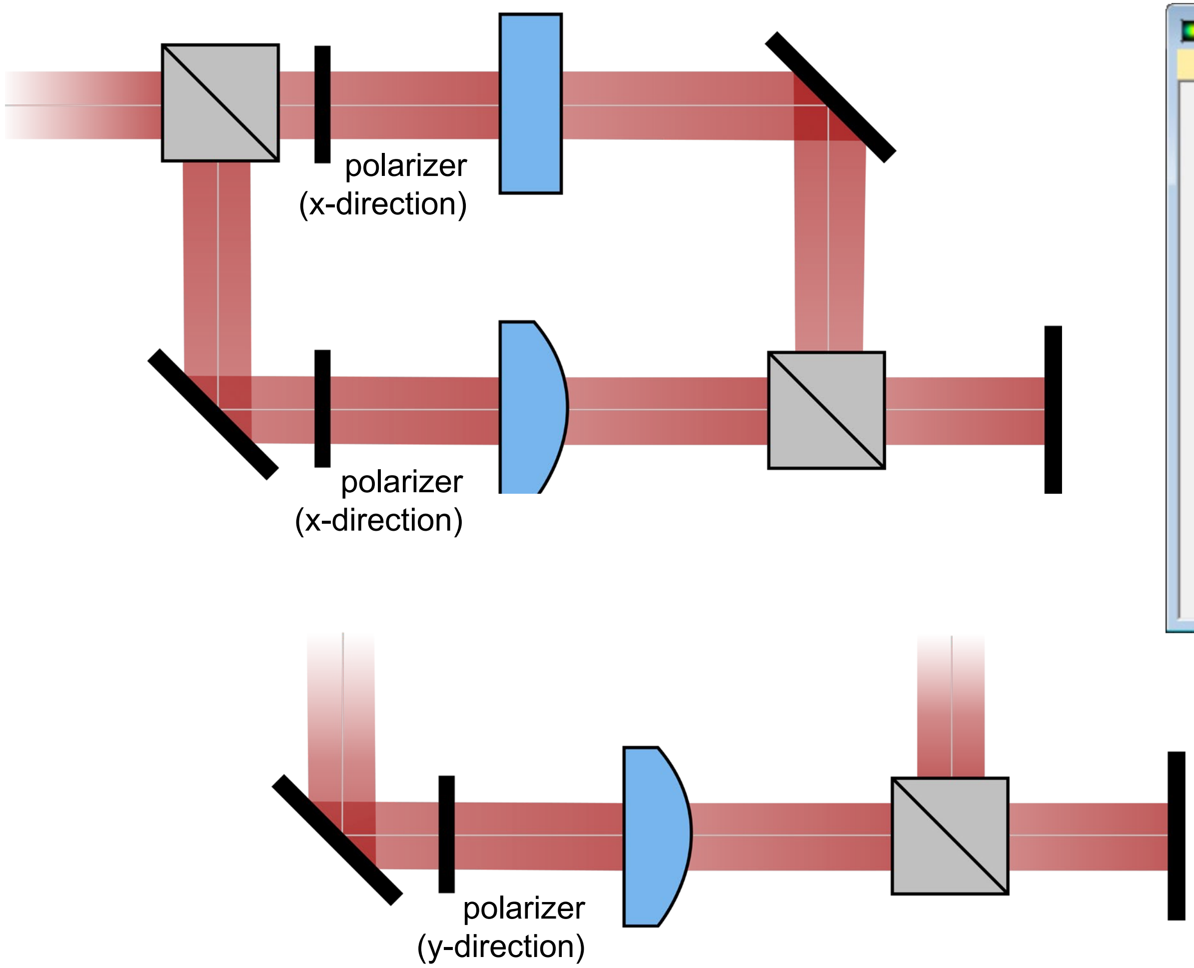
Interference Pattern Changes with Polarizer Rotation

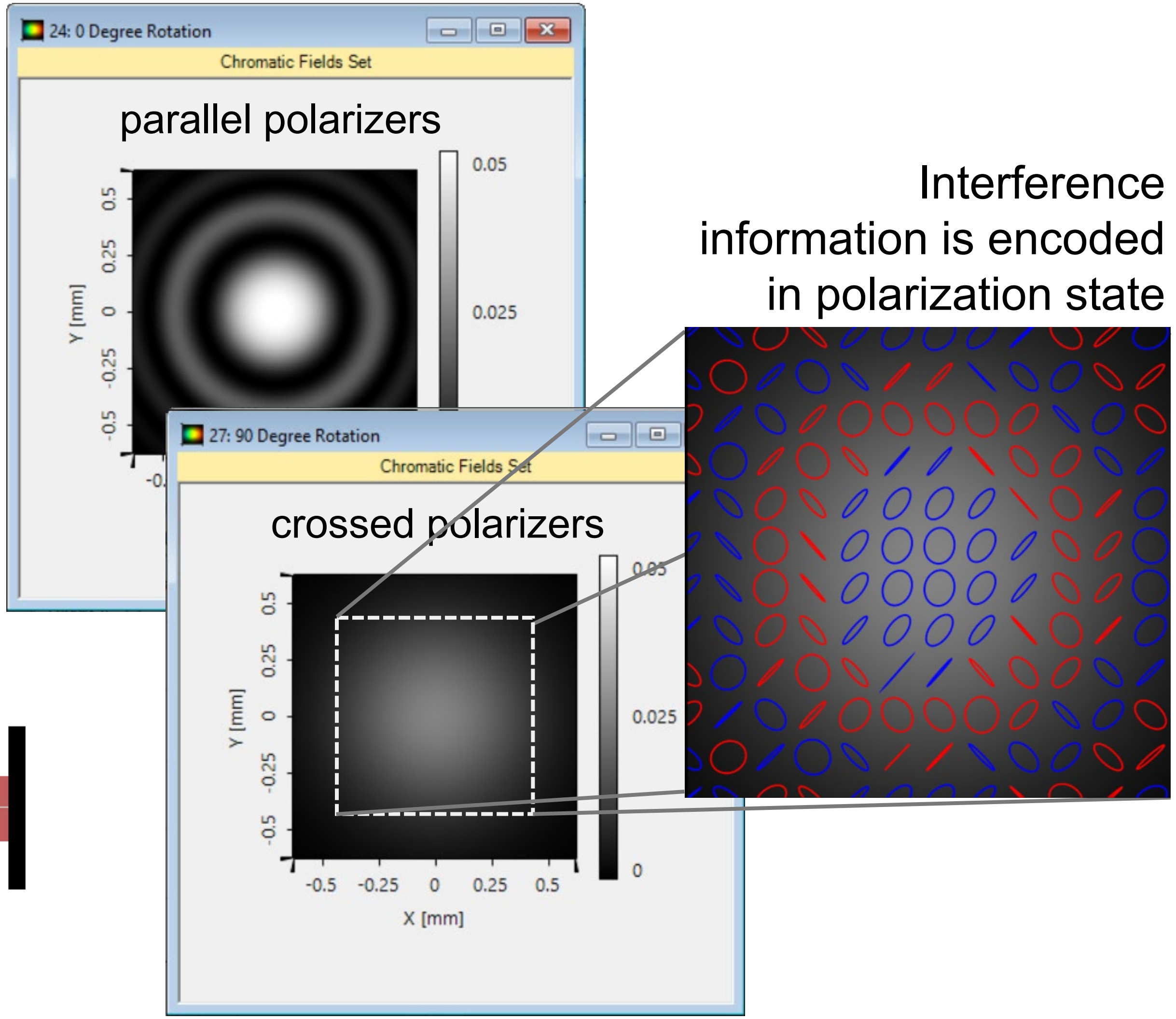




Fringe contrast changes with polarizer rotation.

Interference Pattern





Interference information is encoded in polarization state

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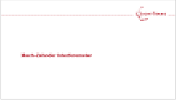
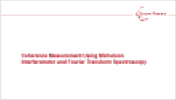
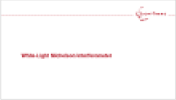
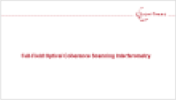
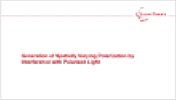
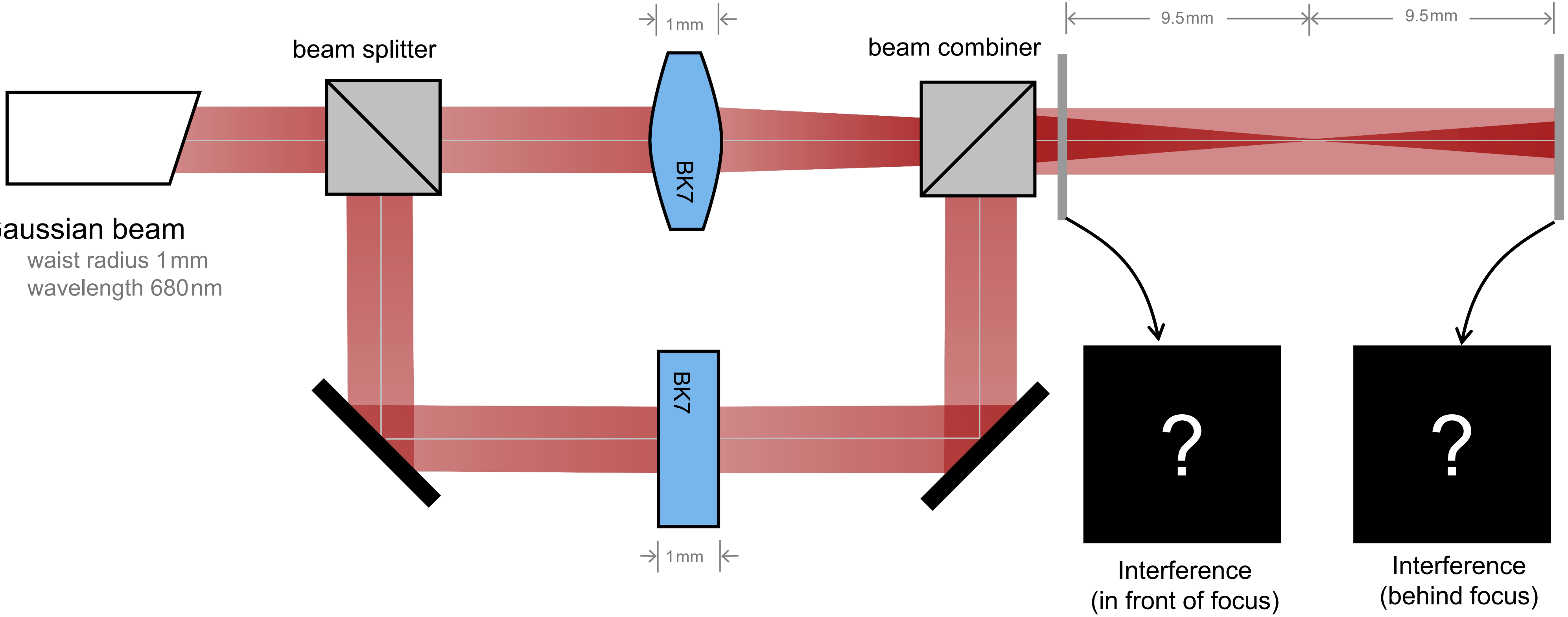




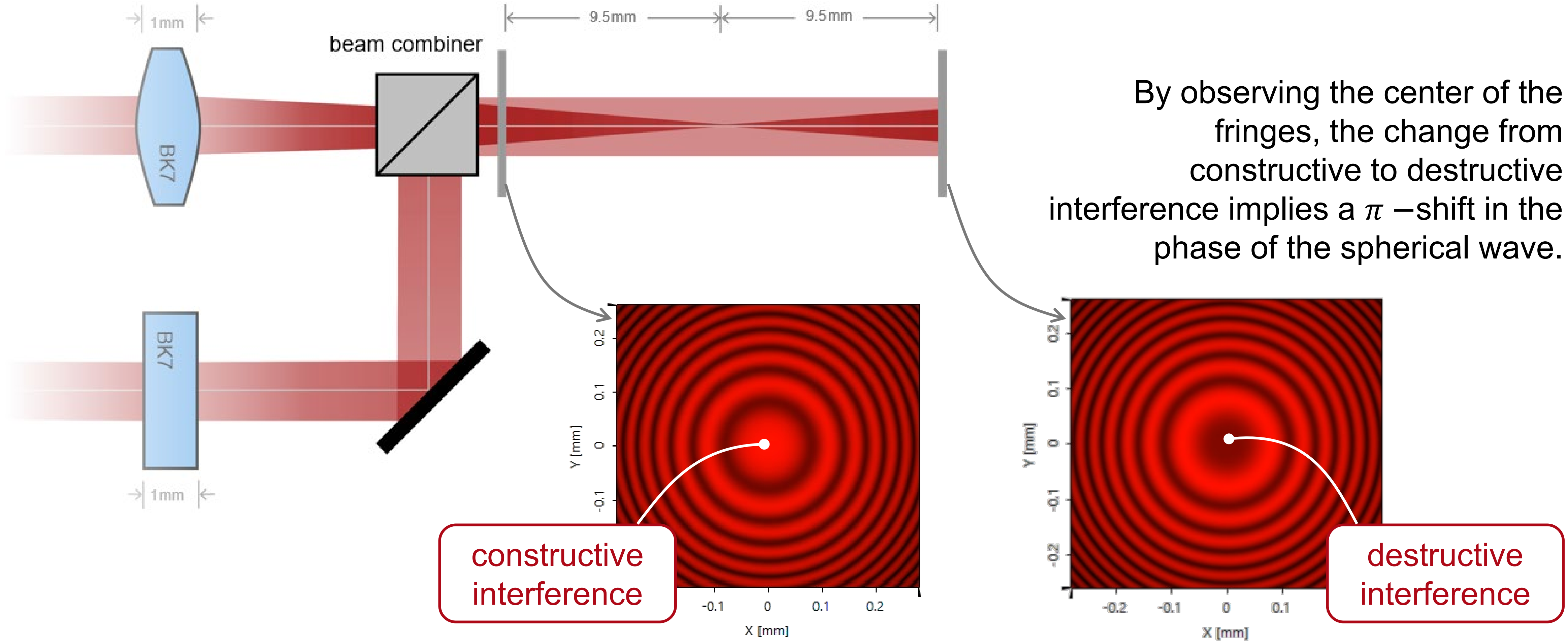

Observation of Gouy Phase Shift in a Mach-Zehnder Interferometer

Modeling Task



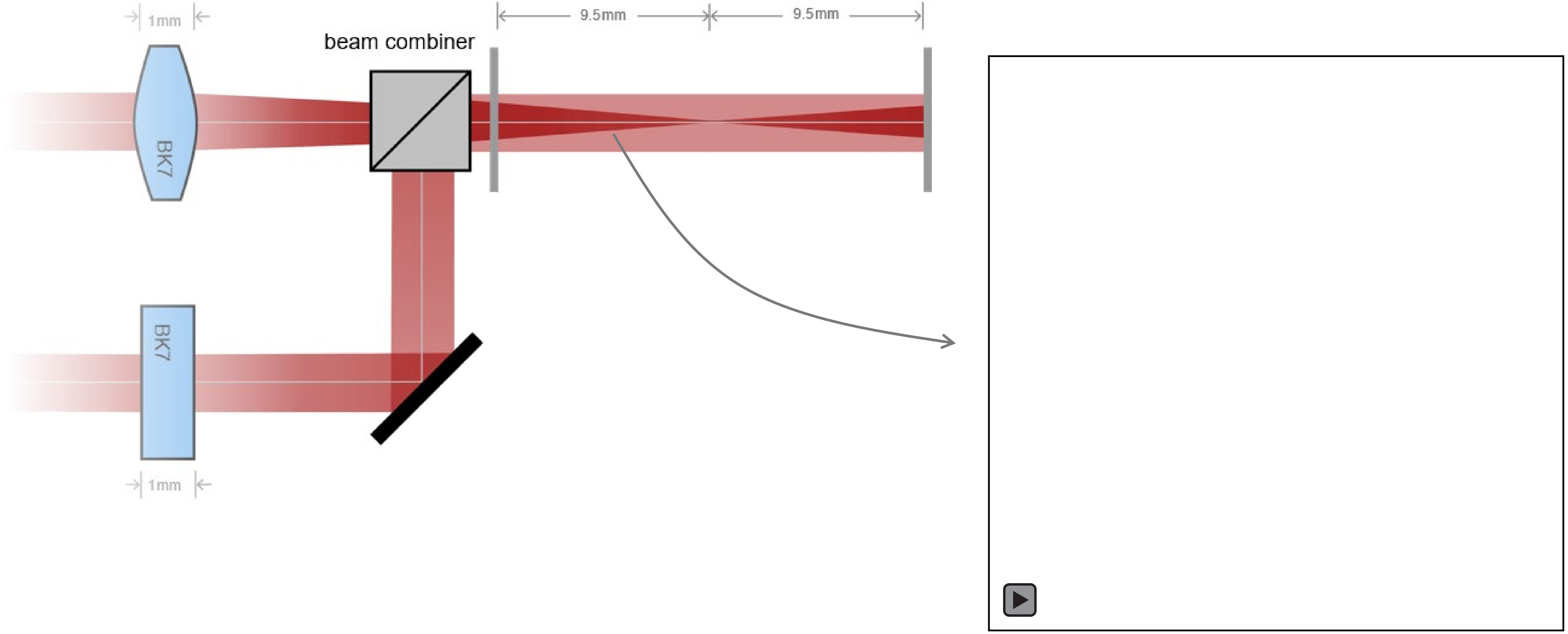
Gaussian beam
- waist radius 1 mm
- wavelength 680 nm

Interference Pattern



By observing the center of the fringes, the change from constructive to destructive interference implies a π −shift in the phase of the spherical wave.

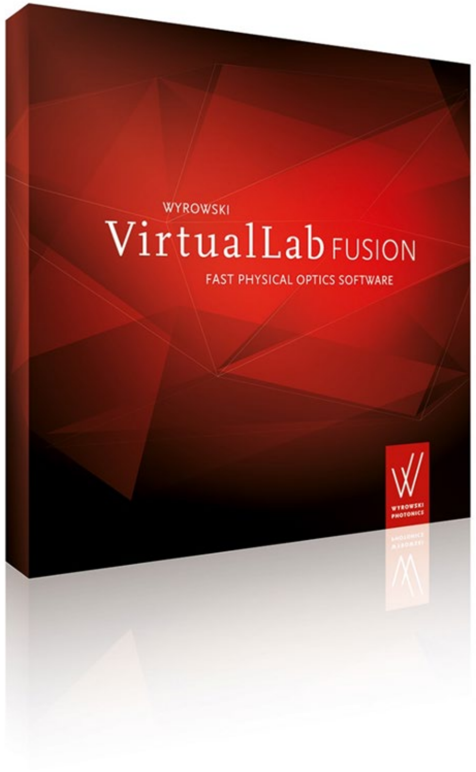
Interference Pattern



Conclusion

- Connecting field solvers enables fast physical-optics modeling
- Channel concept allows non-sequential physical-optics modeling

High flexibility for physical-optics analysis of optical interferometers!



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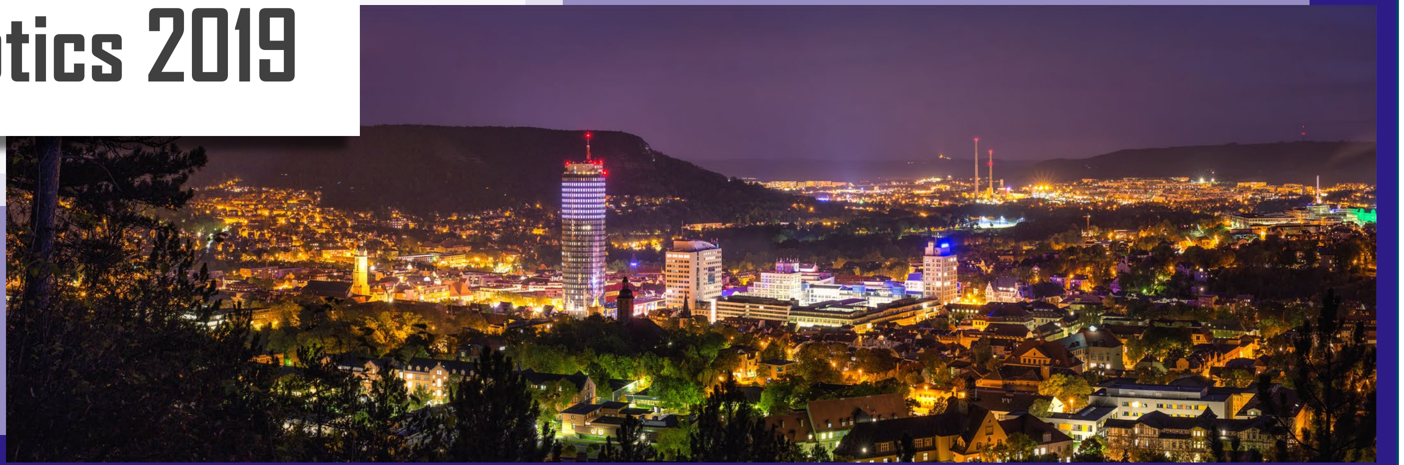

Guest of Honor & Plenary Speaker:

Bernard Kress (Microsoft, USA)

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Invited Speakers

Benfeng Bai, Tsinghua University, China

Sven Burger, Zuse Institute Berlin, Germany

Andreas Erdmann, Fraunhofer IISB Erlangen, Germany

Patrice Genevet, Université côte d'azur, France

Michael A. Golub, Tel Aviv University, Israel

Tommi Hakala, University of Eastern Finland, Finland

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Thank You!