Calibration of Fourier domain short coherence interferometer for absolute distance measurements

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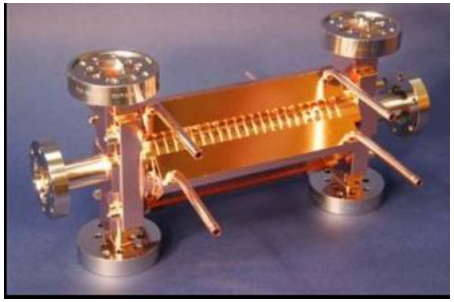
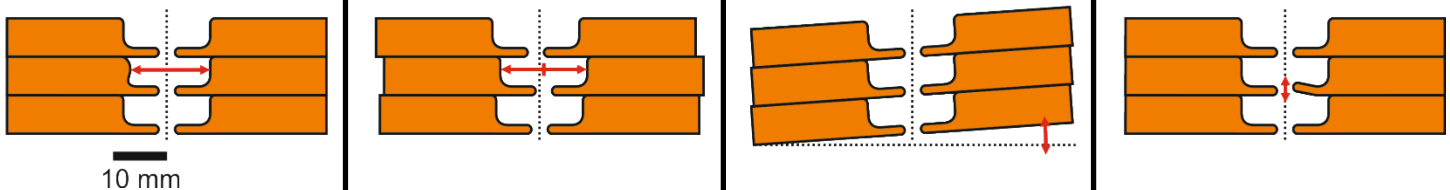
Introduction

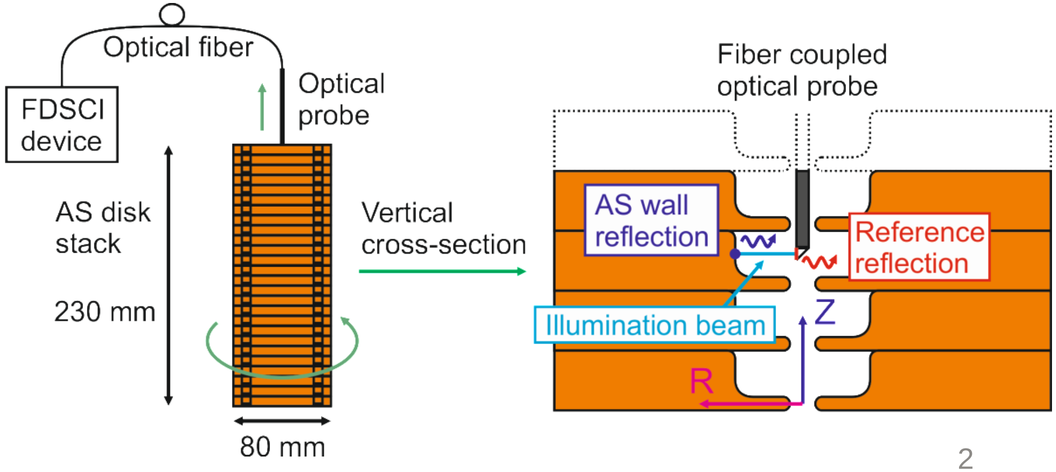


- Accelerating Structures (AS) comprising OFE Cu disks undergo permanent thermo-mechanical deformations during assembly and RF operation.
- These deformations result in micron-level shape errors in AS.

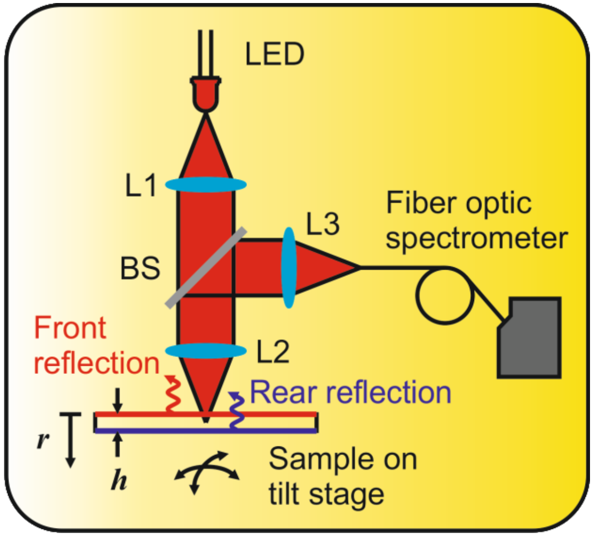


	Error in iris shape	Transversal offset	Tilt	Iris deformation
Shape error				
Tolerance	1 µm	5 µm	140 µrad	

- Sub-micron accuracy across 10 mm measurement range is required.
- Fourier Domain Short Coherence Interferometry (FDSCI) -technique



Design A Setup

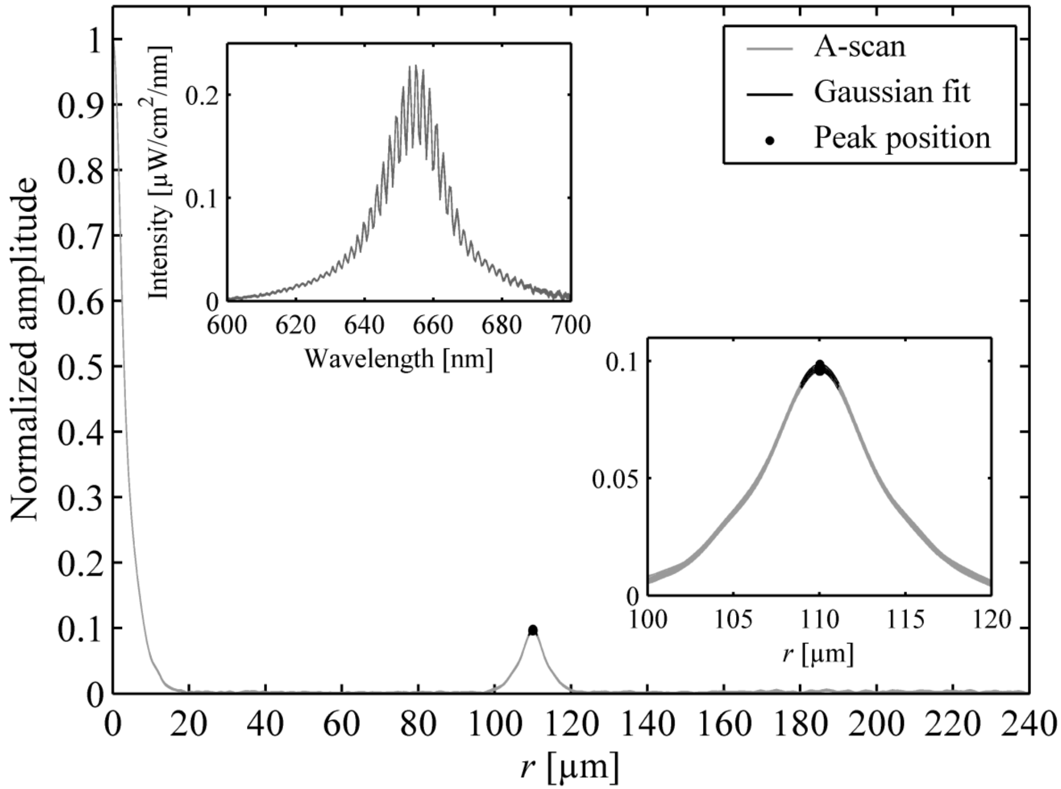


- Design A aims to verify micron accuracy of FDSCI method.
- LED light source (L-793SRC-E, Kingbright, λ_0 = 655 nm, $\Delta\lambda$ = 22 nm)
- Visible range fiber optic spectrometer (HR2000, Ocean Optics, spectral resolution $\delta\lambda$ = 0.44 nm) captures a spectral interferogram.

Measurement range $$R_{max} = \frac{\lambda_0^2}{4n_{air}\delta\lambda}$$

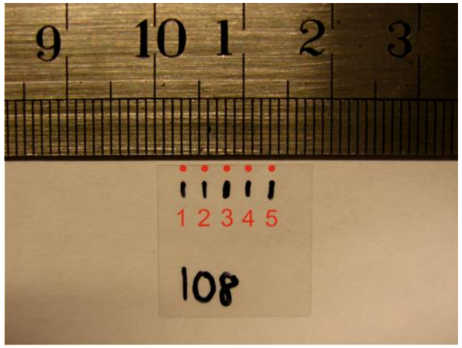
- Expect 240 µm measurement range R_{max}.

A-scan analysis



- Optical thickness (h) of the sample determined as the peak position of a Gaussian fit to the interference peak.
- In 100 A-scans, the repeatability better than 0.2 µm (2σ standard uncertainty)
- Axial resolution 0.002 µm

Calibration



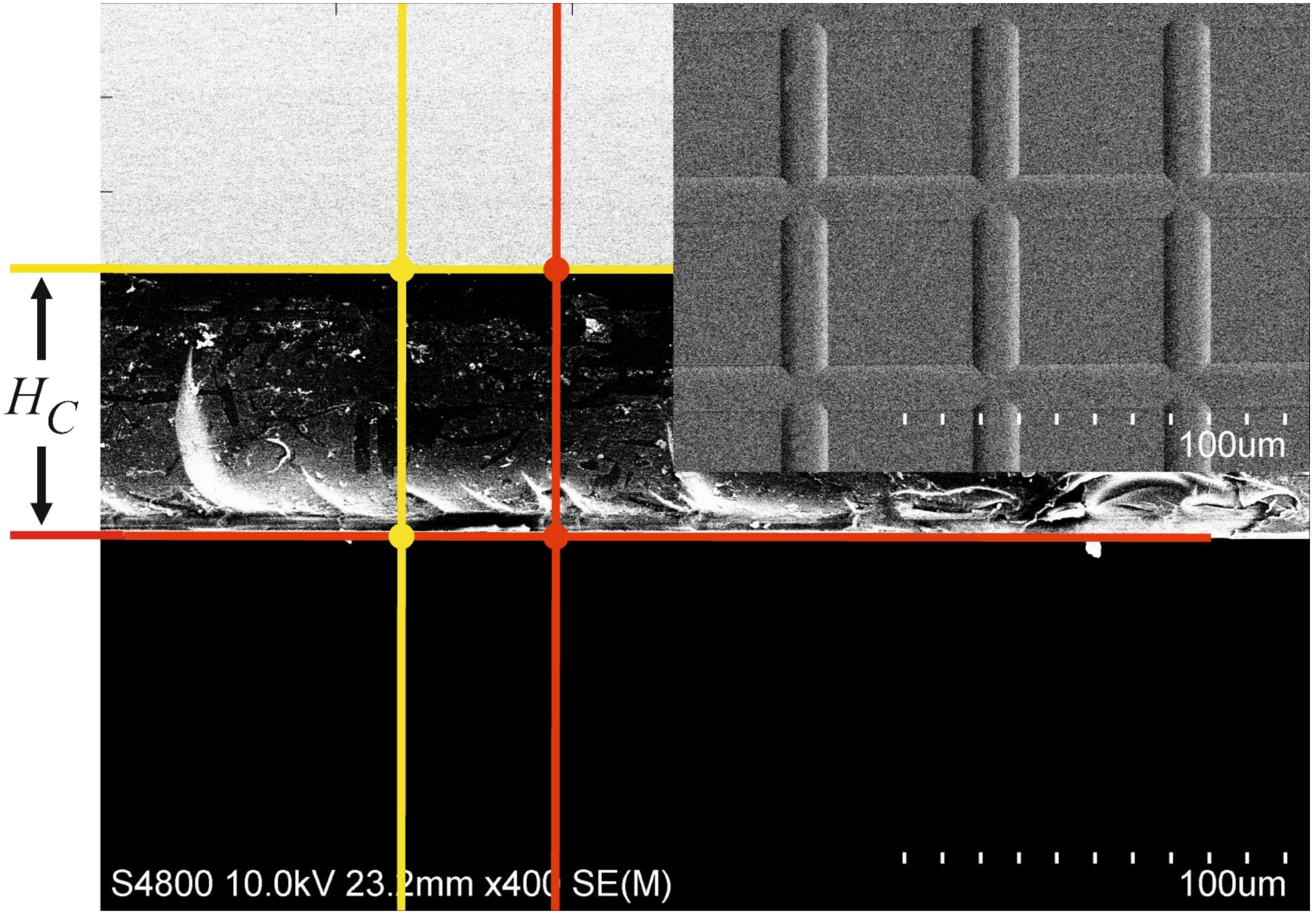
- FDSCI setup calibrated by comparing the optical thickness of five individual calibration samples to the certified geometric thickness.

- Two plastic thickness standards (Check Line, CPS-100)
  - #11441: (11 ± 1) µm
  - #11442: (23 ± 1) µm

- Three standard thickness cover slips (Schott, D 263 M)
  - #00, #0, and #1

- Complementary refractive indices measured using polarometer (Horiba Jobin-Yvon, UVISEL-VASE).

Geometric thickness of cover slips



- Scanning Electron Microscope (SEM) Hitachi S4800
- SIRA SEM S170 calibration specimen (19.7 lines/mm, 1% accuracy)

Measurement bias and uncertainty budget

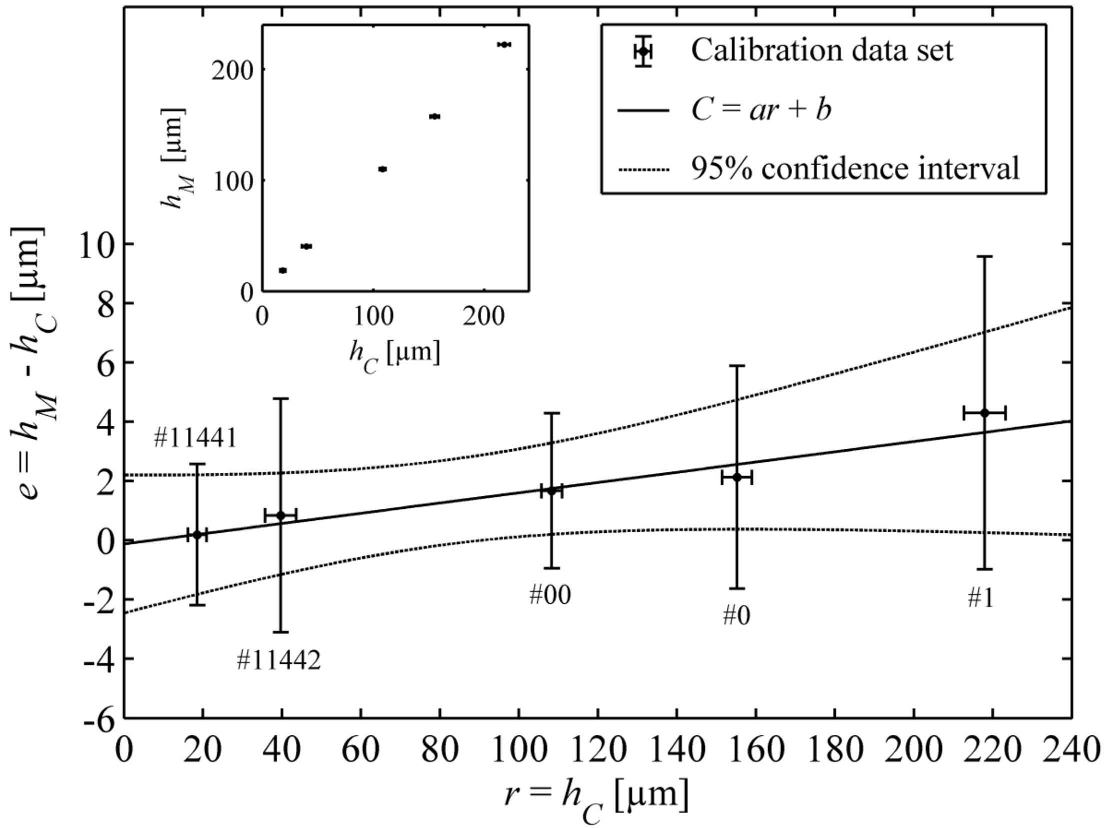
- Measurement bias: $e = h_M - h_C = h\left(1 + \theta_h^2/2\right) - H_C n(1 + \theta_H^2/2)(1 + \alpha\Delta T)$

Uncertainty budget for #00 cover slip sample.

Uncertainty component		Unit	Nominal value	Standard uncertainty $u(x_i)$	Sensitivity coefficient $\lvert c_i \rvert = \left\lvert \frac{\partial f}{\partial x_i} \right\rvert$	Uncertainty contribution $u_i(y) = \lvert c_i \rvert u(x_i)$ [µm]
Optical thickness	h	µm	110.01	0.14	$1 + \theta_h^2/2$	0.14
Angular error in h	θ_h	mrad	7.0	4.0	$h\theta_h$	3.1×10^{-3}
Calibrated geometric thickness	H_C	µm	71.49	0.42	$n(1+\theta_H^2/2)(1+\alpha\Delta T)$	0.64
Angular error in H_C	θ_H	mrad	1.7	1.0	$H_C n \theta_H (1+\alpha\Delta T)$	1.9×10^{-4}
Refractive index	n	-	1.516	0.016	$H_C(1+\theta_H^2/2)(1+\alpha\Delta T)$	1.1
Coefficient of thermal expansion	α	10^{-6} K^{-1}	7.2	0.4	$H_C n(1+\theta_H^2/2)\Delta T$	2.7×10^{-5}
Temperature between h and H_C	ΔT	°C	-0.6	0.8	$H_C n(1+\theta_H^2/2)\alpha$	6.4×10^{-4}

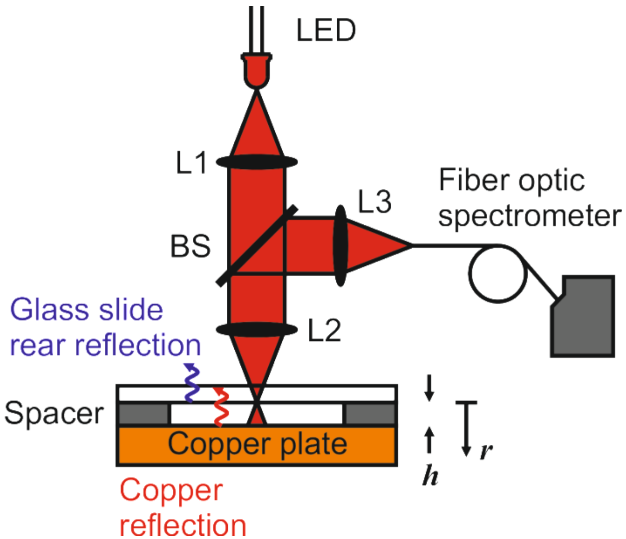
Calculated quantity		Function	Nominal value [µm]	Standard uncertainty $u_c(y) = (\sum_{i=1}^{N} u_i^2(y))^{1/2}$ [µm]	Expanded uncertainty $U = 2u_c(y)$ [µm]
Measured optical thickness	h_M	$h(1+\theta_h^2/2)$	110.01	0.15	0.30
Calibrated optical thickness	h_C	$H_C n(1+\theta_H^2/2)(1+\alpha\Delta T)$	108.3	1.4	2.8
Bias	e	$h_M - h_C$	1.7	1.4	2.8

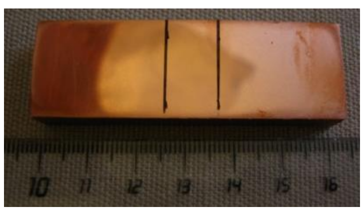
Calibration function and
95% confidence level system uncertainty

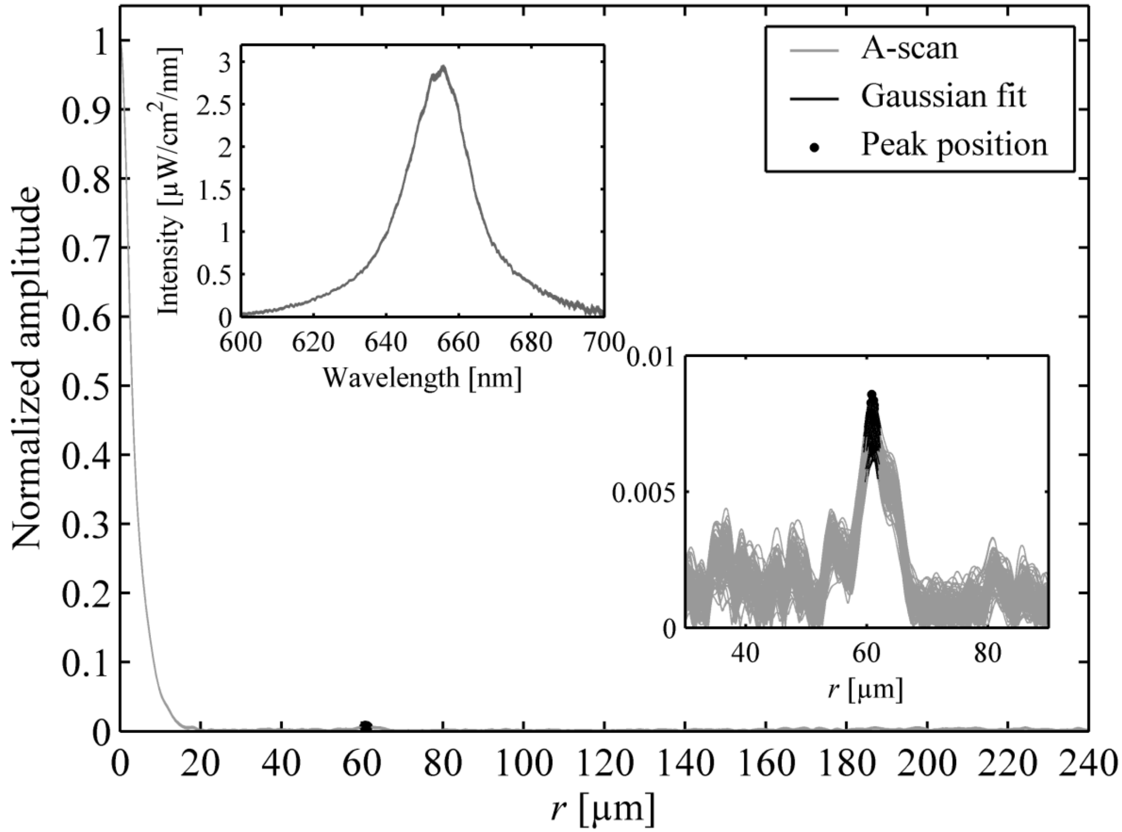


- Calibration function $C = (0.017r - 0.1)$ µm
- 95% confidence level system uncertainty $(6.3 \times 10^{-3}r + 2.4)$ µm (enveloped)
- Article on calibration in preparation.

Example copper measurement



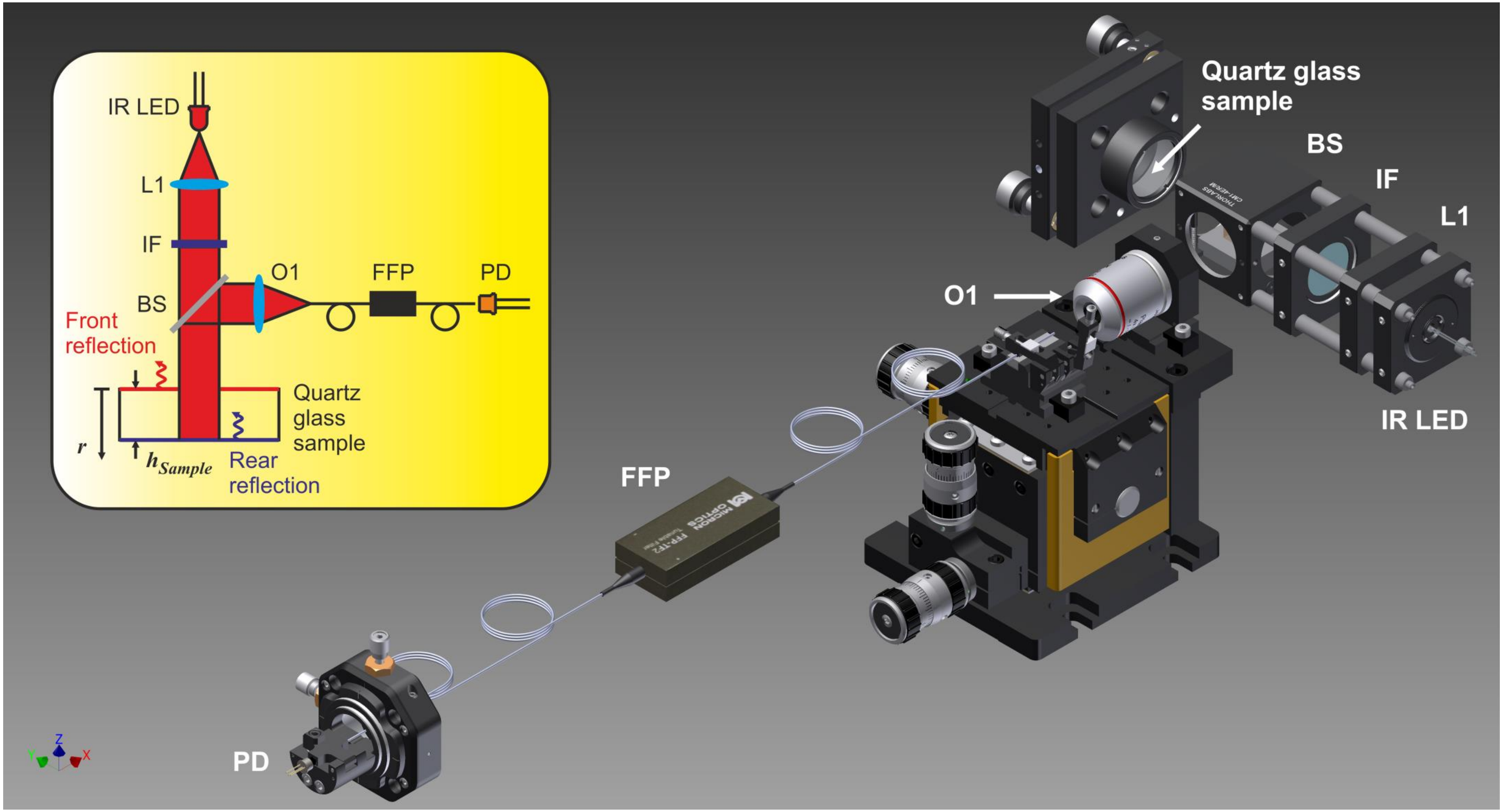




- Optical distance between glass slide rear surface and copper surface h = (60.927 ± 0.021) µm. T = (20.7 ± 0.6) °C, H_R = (32.5 ± 1.7)%.
- Calibrated optical distance: $h_C = h - C(h)$ = (60.0 ± 2.8) µm with 95% confidence level

Design B setup

Fiber Fabry-Perot spectrometer to reach 10 mm measurement range



Conclusions

- FDSCI calibrated for micron accuracy absolute distance measurements.
  - Accuracy could be enhanced using < 1‰ uncertainty dimension standards.
- FDSCI can be used to measure copper.
  - Coherence could be increased tuning the sample tilt.
  - Next the FDSCI will be tested to determine height of ultra-precisely machined steps on an OFE Cu disc.
- To reach the required 10 mm measurement range we will upgrade our setup with a fiber Fabry-Perot spectrometer.

Thank You

Calibration data set

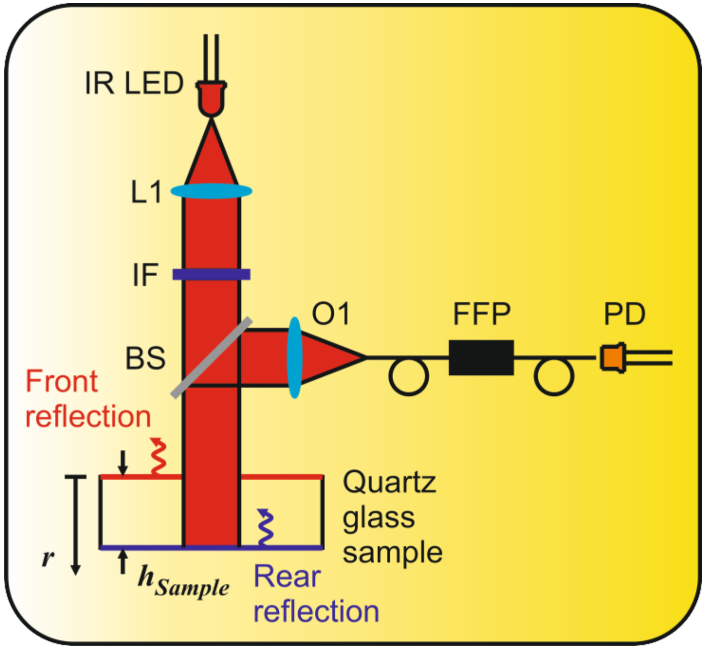
Calibration data set. Uncertainties reported represent 1σ standard uncertainties.

Calibration sample		Optical thickness h [µm]	Angular error in h θ_h [mrad]	Calibrated geometric thickness H_C [µm]	Angular error in H_C θ_H [mrad]	Refractive index n [-]	Coefficient of thermal expansion α [10^{-6} K^{-1}]	Temperature between h and H_C ΔT [°C]
Check Line CPS-100	#11441	18.765 ± 0.078*	7.0 ± 4.0**	11.0 ± 0.6**	-	1.689 ± 0.061*	-+	1.5 ± 1.3**
	#11442	40.53 ± 0.19*	7.0 ± 4.0**	23.0 ± 0.6**	-	1.726 ± 0.074*	-+	1.4 ± 1.3**
Schott D 263 M	#00	110.01 ± 0.14*	7.0 ± 4.0**	71.49 ± 0.42*	1.7 ± 1.0**	1.516 ± 0.016*	7.2 ± 0.4**, ++	-0.6 ± 0.8**
	#0	157.38 ± 0.13*	7.0 ± 4.0**	101.77 ± 0.61*	1.7 ± 1.0**	1.526 ± 0.016*	7.2 ± 0.4**, ++	-3.2 ± 0.8**
	#1	222.26 ± 0.19*	7.0 ± 4.0**	144.15 ± 0.87*	1.7 ± 1.0**	1.512 ± 0.016*	7.2 ± 0.4**, ++	-0.9 ± 0.8**

*Type A uncertainty evaluation (ISO Guide to the expression of uncertainty in measurement).
**Type B uncertainty evaluation, uniform distribution assumed (ISO Guide to the expression of uncertainty in measurement).
+The specification of Check Line CPS-100 includes the thickness variation due to thermal expansion within temperature (21 ± 2) °C.
++α from the datasheet of Schott D 263 M, 10% maximum variation assumed.

Design B

Goal to reach 10 mm measurement range



- NIR LED (LED1550-35K42, Roithner Lasertechnik) + interferense filter (IF) (NIR01-1550/3-25, Semrock) ⇒ $\Delta\lambda$ = 8.8 nm centered at λ_0 = 1550 nm
- Tunable fiber Fabry-Perot (FFP) filter (FFP-TF2, Micron Optics) combined with photodetector (PD) (PT511-2, Roithner Lasertechnik) captures the spectral interferogram.
  - 23.2 nm free spectral range (FSR) at λ_0 = 1550 nm, $\delta\lambda$ = 0.025 nm
- Expect 20 mm axial depth range r_{max} in air.
- 1 – 10 mm quartz glass samples