Broadband Interferometry

A non-contact optical method for measuring the thickness of transparent thin films and coatings

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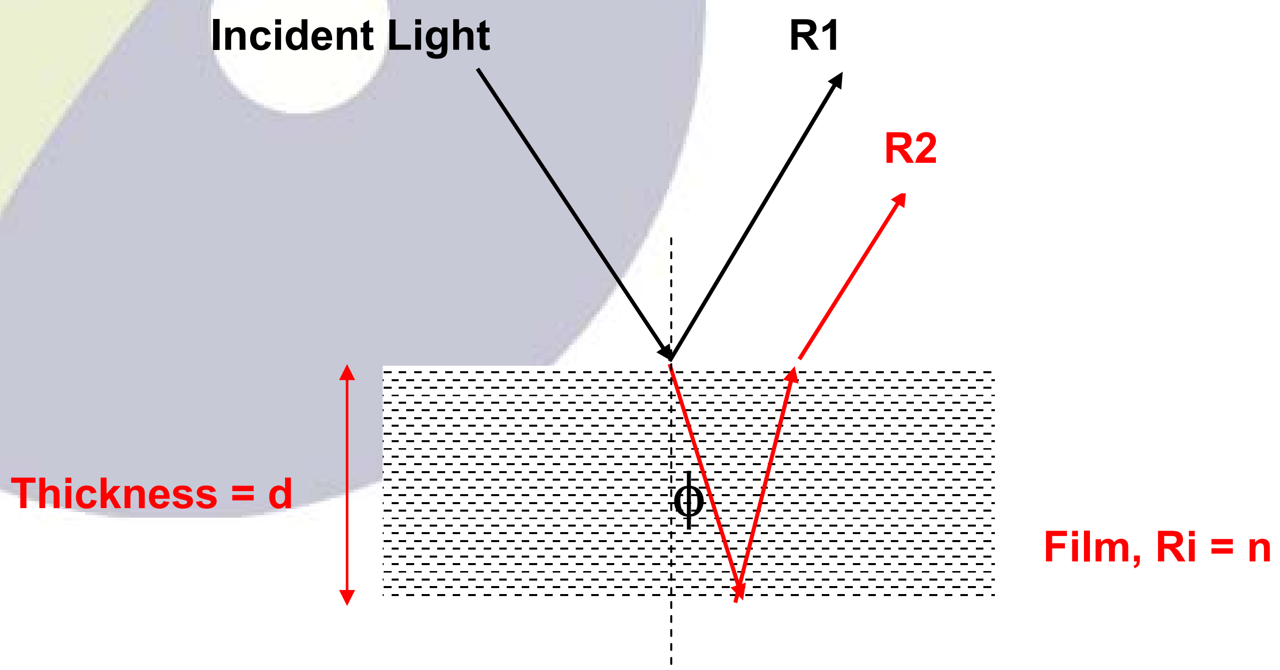
Overview Of Talk

- Basis Of Measurement.
- Thin Film Thickness Calculation.
- Impact of refractive index.
- Accuracy
- Application to multi-layer films.
- Reflection system overview.
- System Limitations.
- Application to in-line measurements.

Thin Film Interference - 1



optical path difference, $\Delta r = n*(2d \cos \phi)$

Thin Film Interference - 2

R1 is phase-shifted on reflection, but R2 is not

if path difference = whole number of wavelengths

- **We will get an intensity minimum or dark fringe**

i.e. if **Δr = $n^*(2d\cos\phi) = m\lambda$** **minimum**

and if **$n^*(2d\cos\phi) = (m + 1/2)\lambda$** **maximum**

where λ **=** wavelength of light

Fringe Counting

If, $\mathbf{2\ n\ d\ cos}\ \phi\ \mathbf{= m}\lambda$ for a particular fringe

a change in film thickness will change the fringe number

i.e. $\mathbf{2n}\ \Delta\mathbf{d\ cos}\ \phi = \Delta\mathbf{m}\ \lambda$

viewed near the normal, $\mathbf{cos}\ \phi = 1$

Therefore $\mathbf{2n}\ \Delta\mathbf{d} = \Delta\mathbf{m}\ \lambda$

Or $\Delta\mathbf{d} = \Delta\mathbf{m}\ \lambda\mathbf{/2n}$

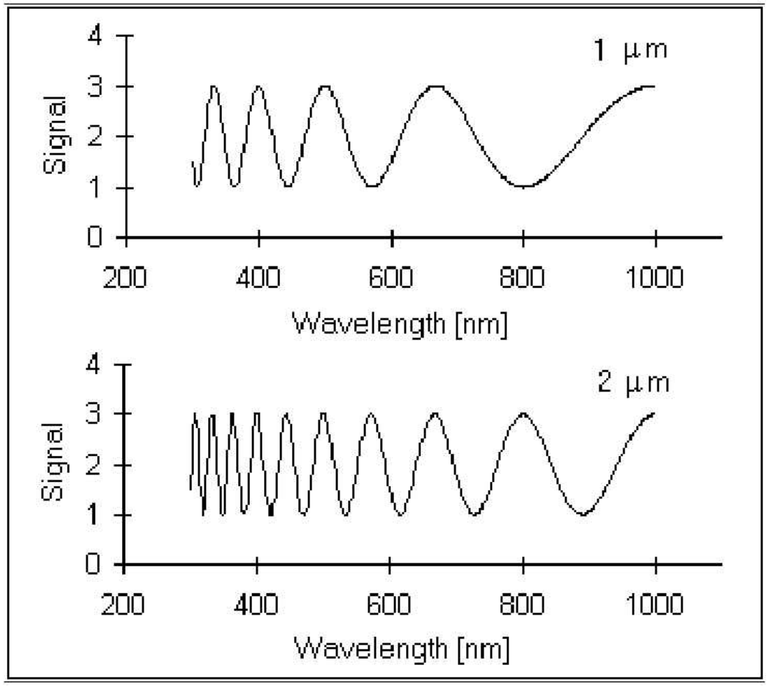
Broadband Interference

- λ has a broad range of values, dependent on the light source and the spectrometer used

- so we express the interference pattern as a function of intensity vs wavelength

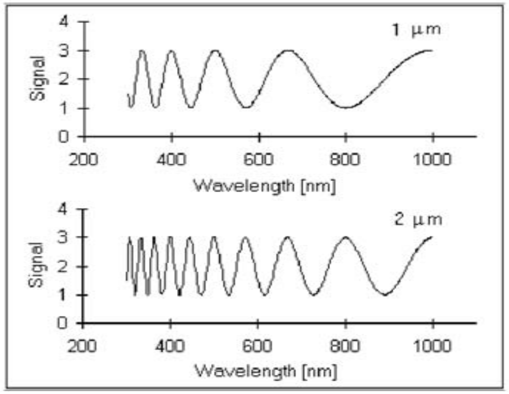
- the solution of this equation gives us film thickness information

Single Layer Interference Patterns



$$I(\lambda) = A + B * \cos [2\pi * \Delta r / \lambda + \Delta\delta]$$

Film Thickness Calculation - 1



$$I(\lambda) = A + B * \cos [2\pi * \Delta r / \lambda + \Delta\delta]$$

(from previous slide)

at each maximum, $\cos [2\pi * \Delta r / \lambda + \Delta\delta] = 1$

or $[2\pi * \Delta r / \lambda + \Delta\delta] = m*2\pi$ where m is an integer

calculate the difference between any two maxima

$$[2\pi * \Delta r / \lambda_2 + \Delta\delta] - [2\pi * \Delta r / \lambda_1 + \Delta\delta] = 2\pi[m_2 - m_1]$$

or $\Delta r[1 / \lambda_2 - 1 / \lambda_1] = m_2 - m_1$

and $\Delta r = 2\, n\, d$ for light normal to the film

Film Thickness Calculation - 2

substituting for $\Delta \mathbf{r}$ we find that

$$\mathbf{d = [m_2 - m_1] / 2n*[\, 1 / \lambda_2 - 1 / \lambda_1]}$$

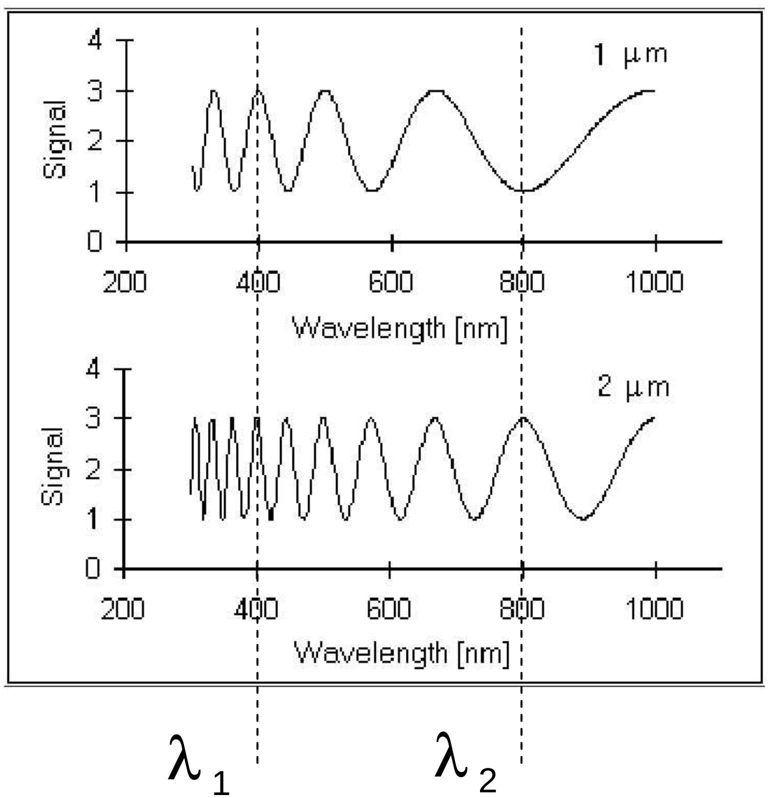
or $$\mathbf{d = [m_2 - m_1]* \lambda_1 * \lambda_2 / 2n\, [\lambda_2 - \lambda_1]}$$

consider the example spectrum shown of the 2um layer

between 400nm and 800nm there are 5 whole wavelengths,

so $[m_2 - m_1] = 5$, $\lambda_1 = 0.4$, $\lambda_2 = 0.8$ (in microns)

Film Thickness Calculation - 3



$[m_2 - m_1] = 5$, $\lambda_1 = 0.4$, $\lambda_2 = 0.8$

$d = 5 * 0.4 * 0.8 / 2 * n * (0.8 – 0.4)$

$d = 1.6 / 0.8 = 2/n$ µm

where n=1, this gives optical thickness, d_o

so **d_o = 2 µm**

Refractive Index

in some applications of optical coating, the preferred parameter to be known is optical thickness, $\mathbf{d_o}$

in most applications, physical thickness **d** is required, where

$$\mathbf{d_o = n*d}$$

but in fact, refractive index n varies with wavelength, according to the Cauchy **dispersion** formula

Cauchy Dispersion Formula

$$n(\lambda) = n0 + B / \lambda^2 + C / (\lambda^2 * \lambda^2)$$

$n(\lambda)$	dispersion
n0	polynomial constant
B, C	polynomial factors
λ	wavelength

for absolute accuracy we need to know n0, B & C, but for many applications

$$n(\lambda) \sim n0$$

Typical Errors due to Dispersion

Example Coating	Wavelength Range		Dev from	Delta %
	400-700nm	700-1000nm	Mean µm	
	µm	µm		
UV cured hardcoat on polycarbonate	7.08	6.86	0.11	1.6
Dipped hardcoat on polycarbonate	15.13	14.65	0.24	1.6
Unspecified coating on PE	13.47	13.37	0.05	0.4
Hardcoating on PET	7.56	7.35	0.11	1.4
Hardcoating on multilayer film	5.46	5.34	0.06	1.1

Automatic Film Thickness Calculation

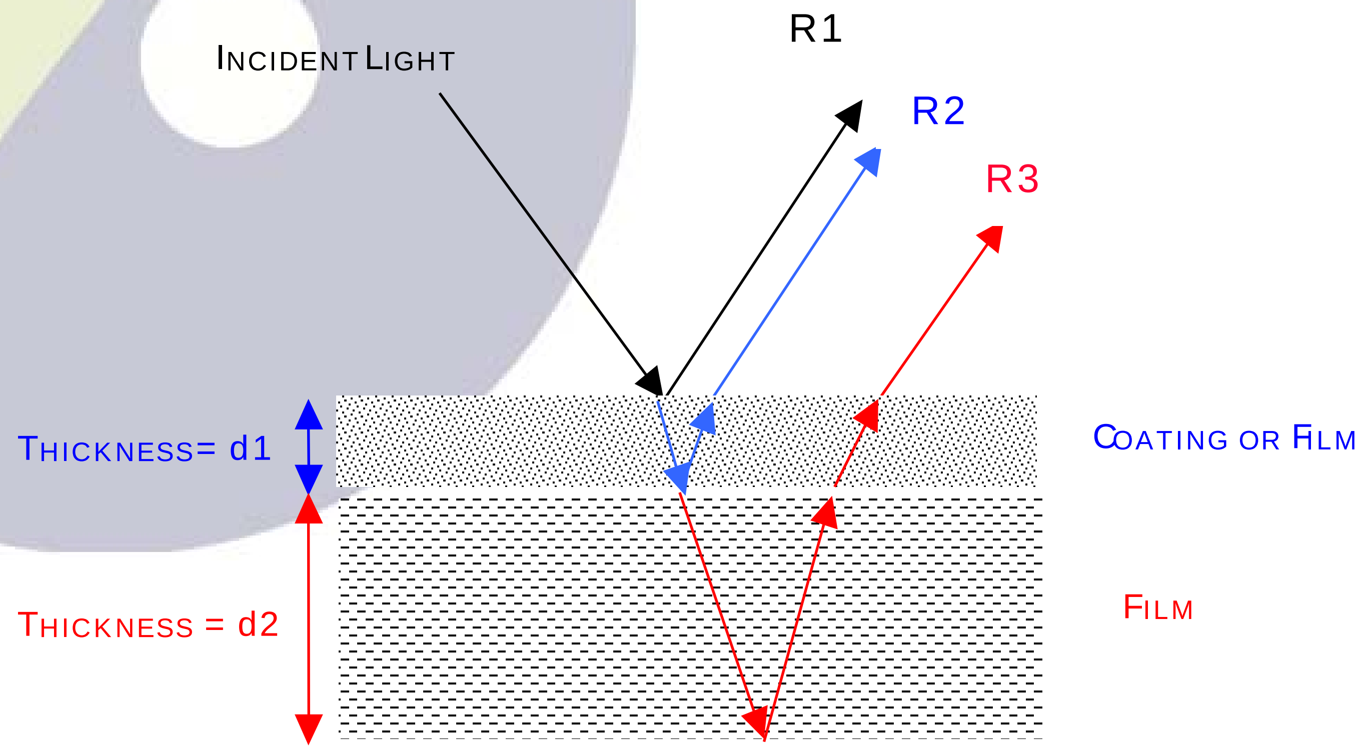
Fast Fourier Transform (FFT) calculation method:

- very fast & suited to computers
- result can be centroided for accurate numerical value
- absolute value without calibration
- ability to resolve complex waveforms into constituent layers (i.e. multilayer films)

Accuracy – Contributing Factors

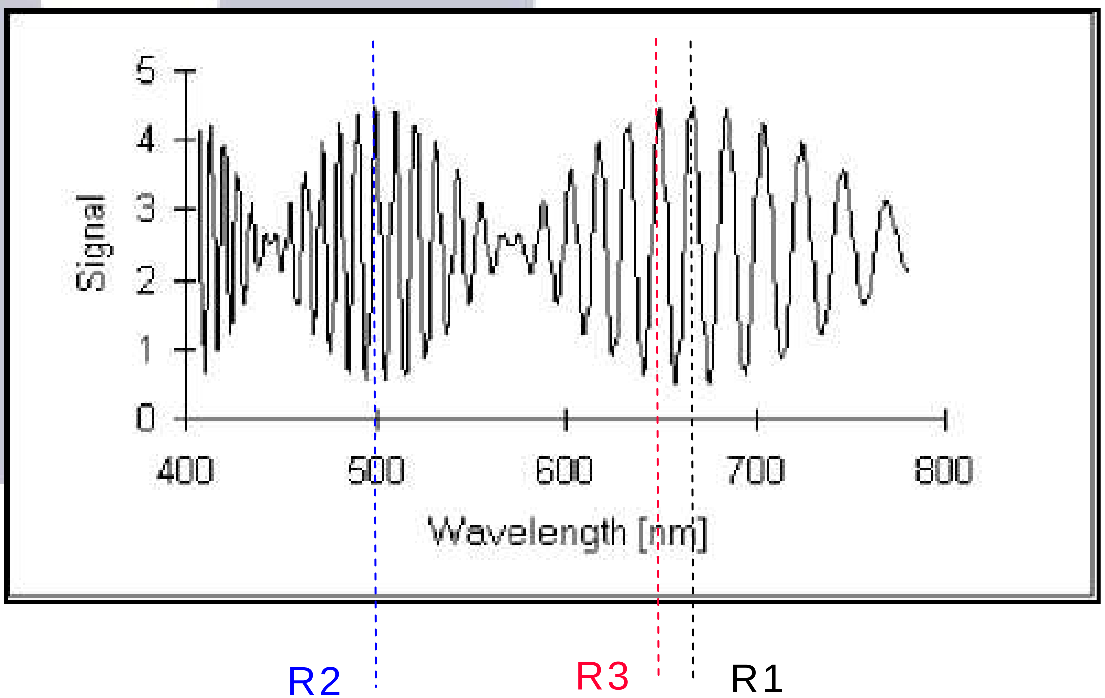
- Spectrometer accuracy < 0.3nm absolute
- FFT & centroid calculation is numerical < 0.1nm
- Test sample variation/spot size
  - Probe diameter = 0.8mm
  - Sample spot size 1-2 mm (if not in contact with sample)
  - Result is centroid value of range of values within spot
- Accuracy of refractive index
  - Variation due to manufacturing process (e.g PET varies between 1.58 and 1.64)
  - Variation due to dispersion (typical error 0.5% – 2.0%)

Multilayer Films



3 possible combinations: R1/R2 = d1, R2/R3 = d2 and R1/R3 = d1+d2

Two-Layer Interference Pattern



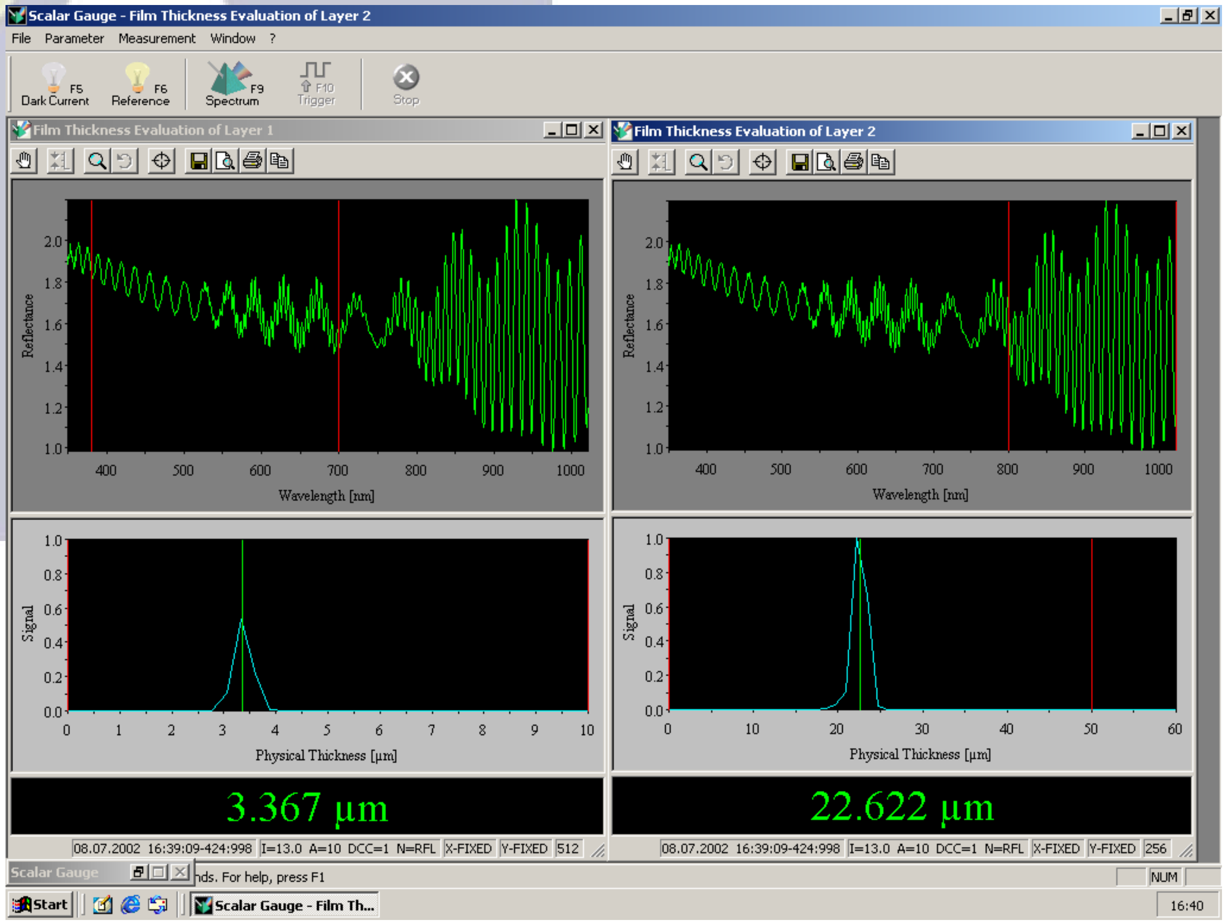
R1/R2 relates to thickness d1, R1/R3 relates to thickness d1+d2
R2/R3 interaction too weak to detect in this example

Reflection System

Reflection System Operation

- Light from upper unit travels down fibre-optic cable and into target sample
- Light reflected off sample and containing interference pattern travels back up cable into spectrometer
- Spectrometer captures interference pattern and converts it into digital data
- Digital data is analysed by the PC and thickness information is extracted and displayed

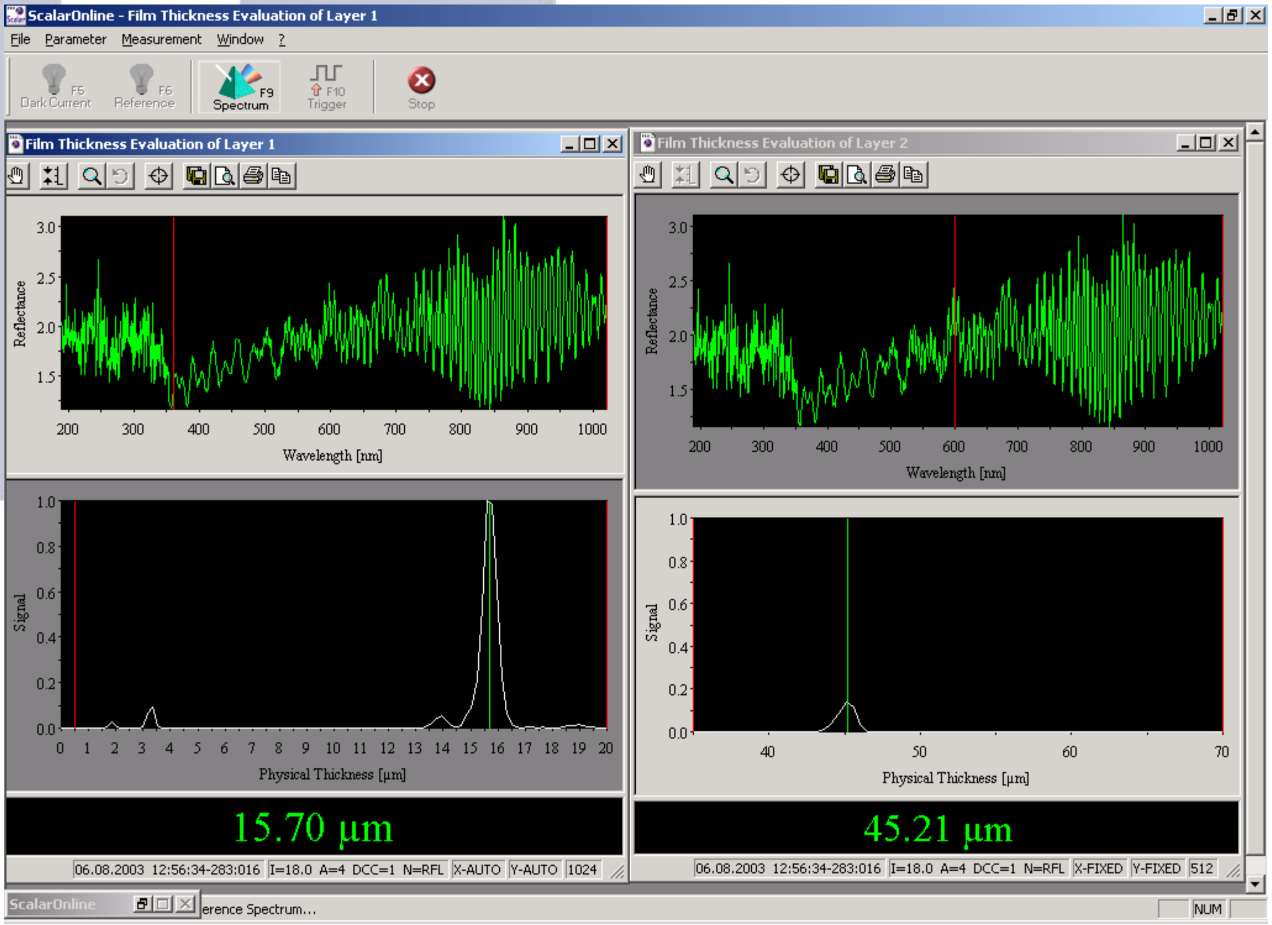
Reflection System Display



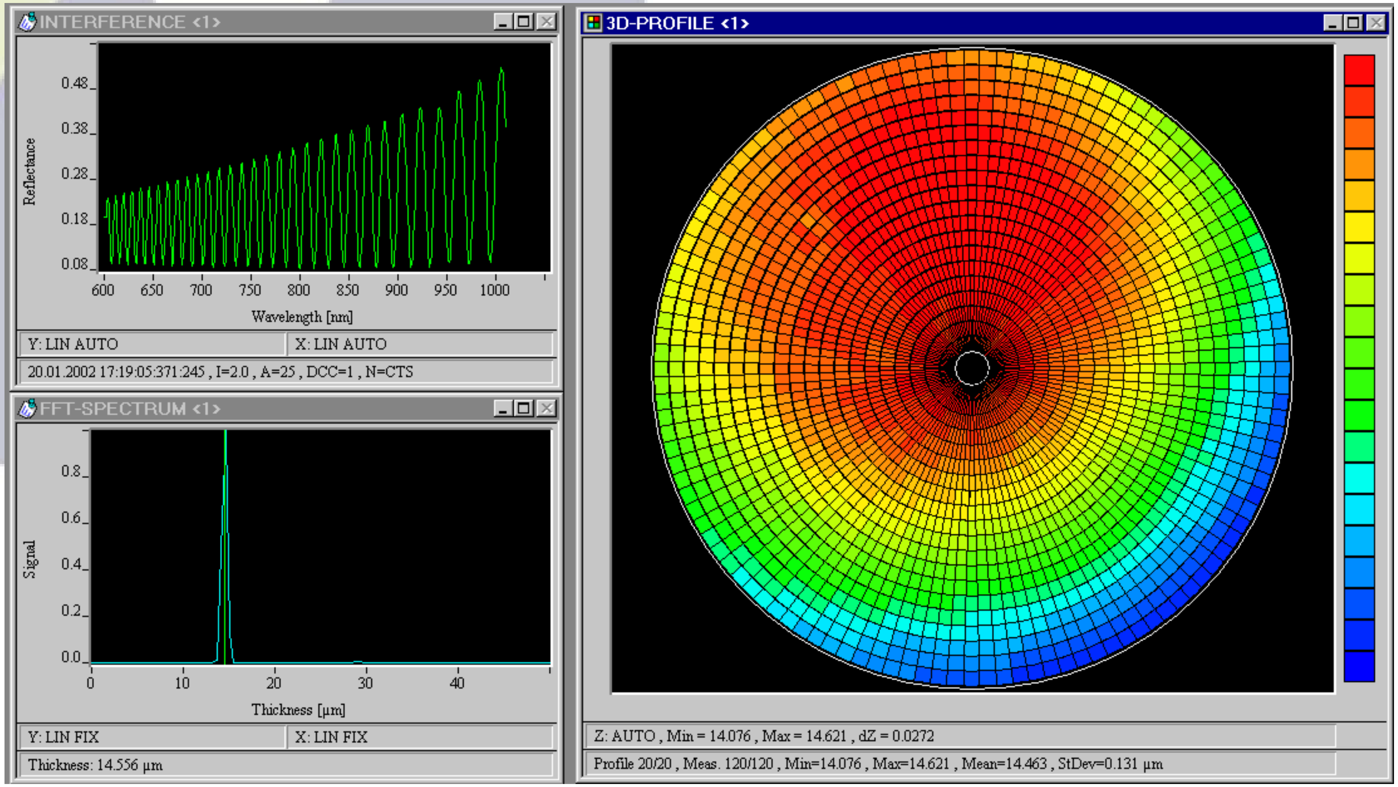
Explanation of Display

- **Top** shows the interferometry pattern plus user-defined max/min wavelengths used for analysis
- **Middle** shows the processed thickness peaks, within user-defined search areas
- **Bottom** shows the calculated results
- **Left and right** screens show two independent FFT analyses of same data, using different user-defined search ranges
- Windows OS allows easy export and storage of sample results

Example of Multilayer Film



CD Coating Profile



Working Limitations

- Test materials MUST be transparent & smooth
  - Rough surfaces do not reflect light coherently
  - Some colouring and limited opacity acceptable
- Need strong internal reflection to work well
  - Adjacent materials of similar Ri will not reflect
- Upper and lower thickness limits determined by thickness algorithm, light source and spectrometer
  - FFT needs 1-2 wavelengths to work well
  - Range of example system is $0.5 < d < 100$ microns
- Number of layers measurable in multi-layer films depends on reflectivity of internal boundaries
  - Accuracy depends on knowledge of refractive index

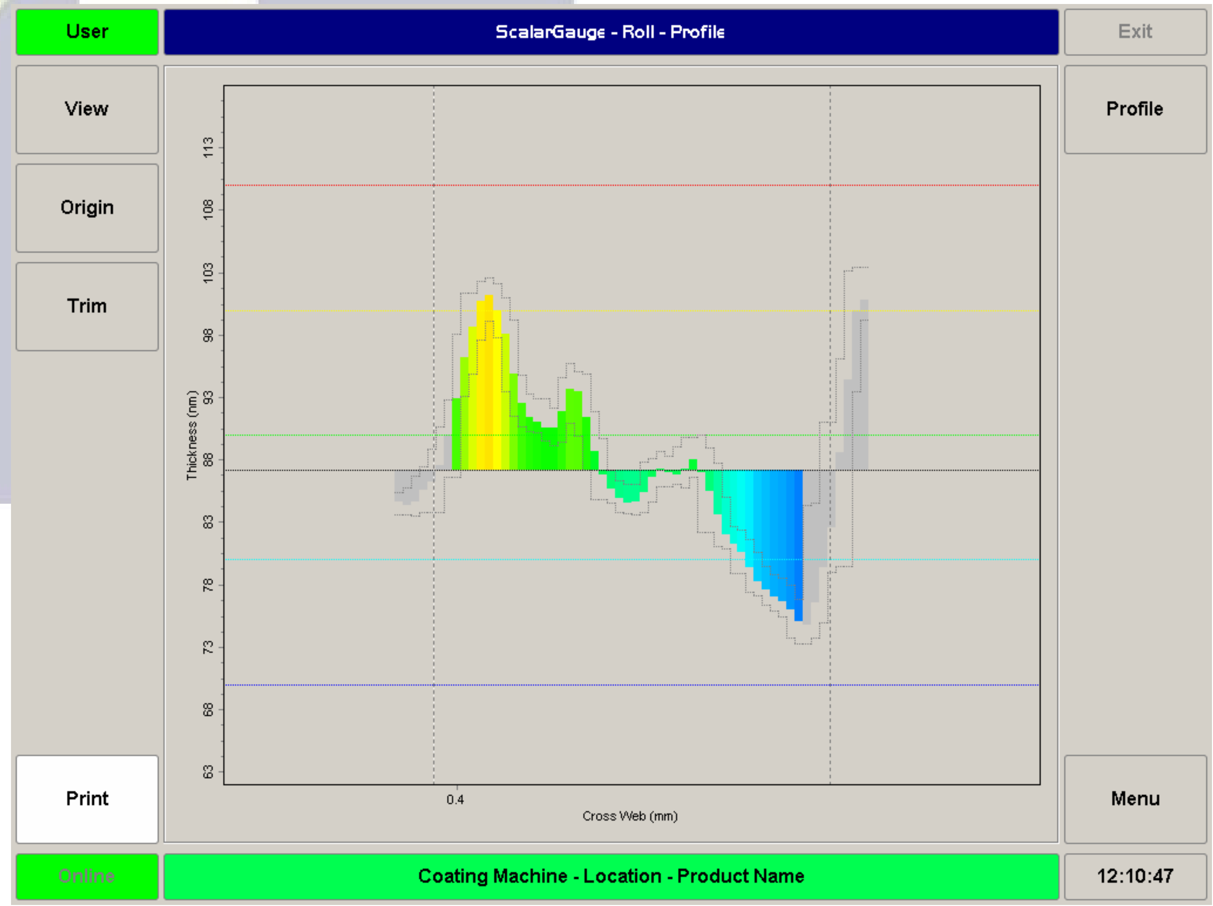
In-Line Operation

- Spectrometer collects light for “Integration Time”
  - typically 10 – 50ms
- Integration Time is set to maximise signal/noise ratio
  - Varies according to material under test
  - Varies with distance of probe to material
- Movement of material during Integration Time “blurs” interference pattern
  - excessive movement will obliterate the interference pattern
- Tests show achievable line speed of around 50m/min (150ft/min)

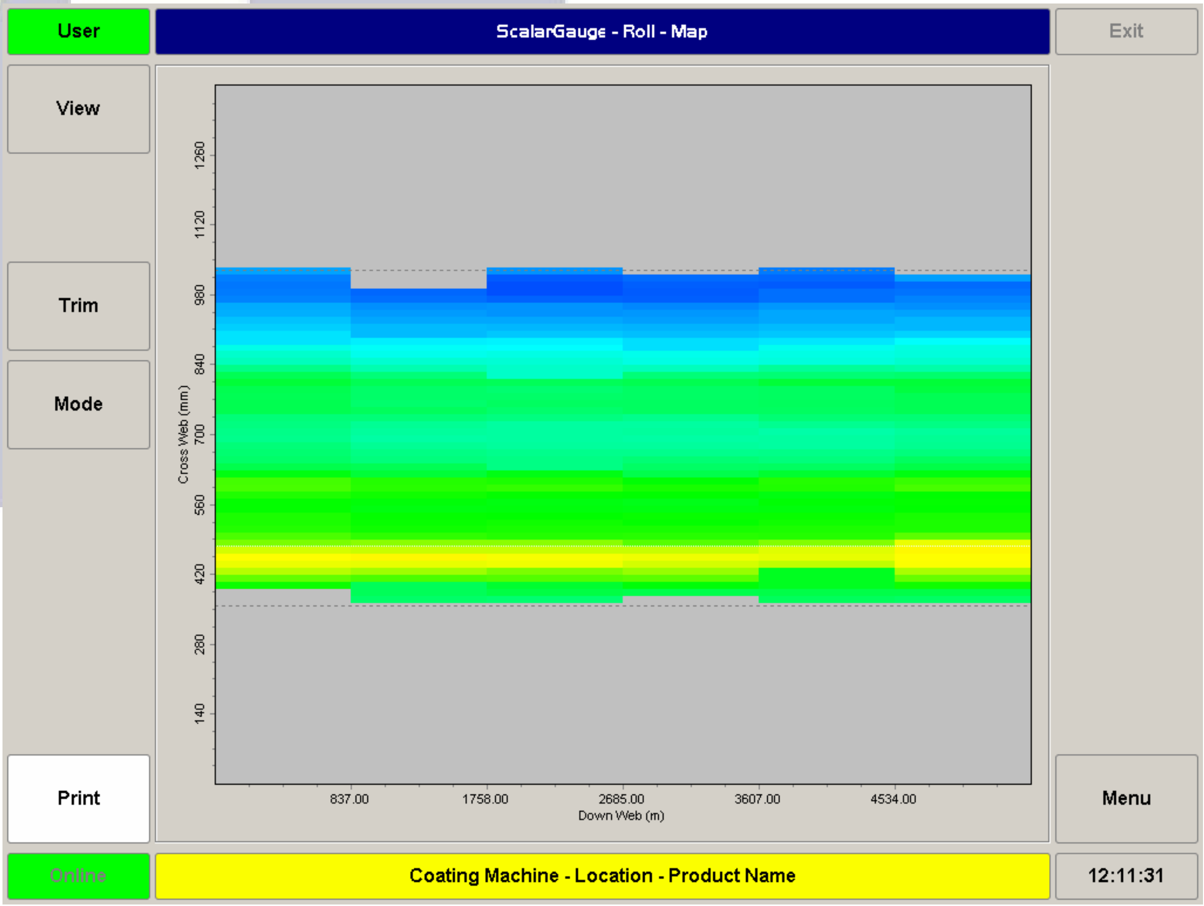
In-Line Instrument

- Similar hardware to off-line instrument
- Different “process control” type software
  - Profile, trend and roll map displays
  - Recipe selection, alarm levels
  - Real-time data export, file storage & archive
  - Integrated high performance scanner
- Web speed limited to ~ 50m/min
- Non-contact, non-nucleonic, passive sensor
  - Possible operation in hazardous areas

Example – Roll Profile Display



Example – Roll Map Display



How to Increase Line Speed

- To increase line speed, must reduce Integration Time
- New spectrometers are faster, more sensitive
- New light sources will deliver more energy
- The right combination of light source and spectrometer will deliver results
- Next target 300m/min

Broadband Interferometry - Conclusion

- For smooth transparent films & coatings only
- A safe, non-contact, non-destructive technique
  - Can be used in hazardous environments
- Fast, absolute measurements
  - No calibration required
- Accuracy only limited by knowledge of Ri
- Excellent results with multi-layer films
- Fast enough for slower in-line processes
  - New developments to improve process speed
- Use in transmission mode to measure vacuum deposited coatings
  - Broadband Optical Monitor