Diffraction-based approaches to the in-situ measurement of dimensional variations in components produced by thermoplastic micro- and nano-embossing

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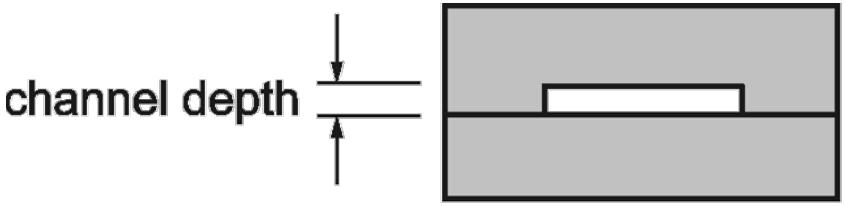
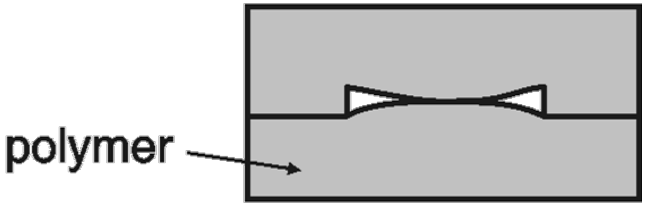
Outline

- **What types of defects do we need to detect?**
- **Why consider diffraction?**
- **Motivation for using tailored diffractive patterns**
- **Two example schemes:**
  - **Depth measurement of channels ~ 1 µm deep**
  - **Detection of incomplete micro-pattern embossing**
- **Future directions**

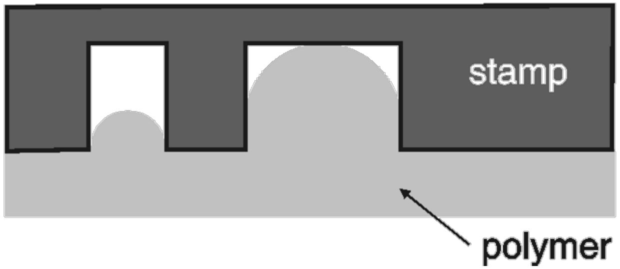
Examples of processing defects in hot embossing



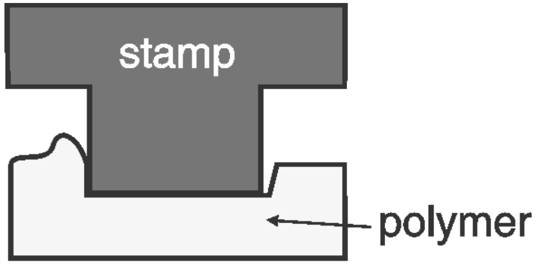
- **Nano-channel depth variation**

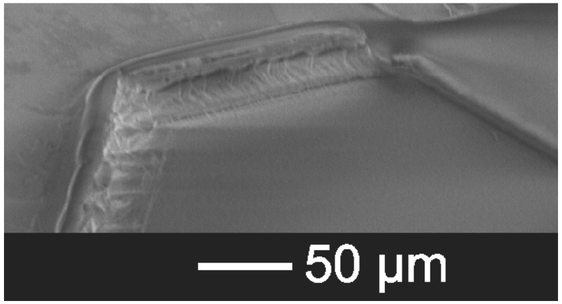


- **Nano-channel collapsing**



- **Incomplete stamp filling**





- **Demolding-related defects**

- **Intra-part non-uniformity**

Requirements of an in-line metrology system

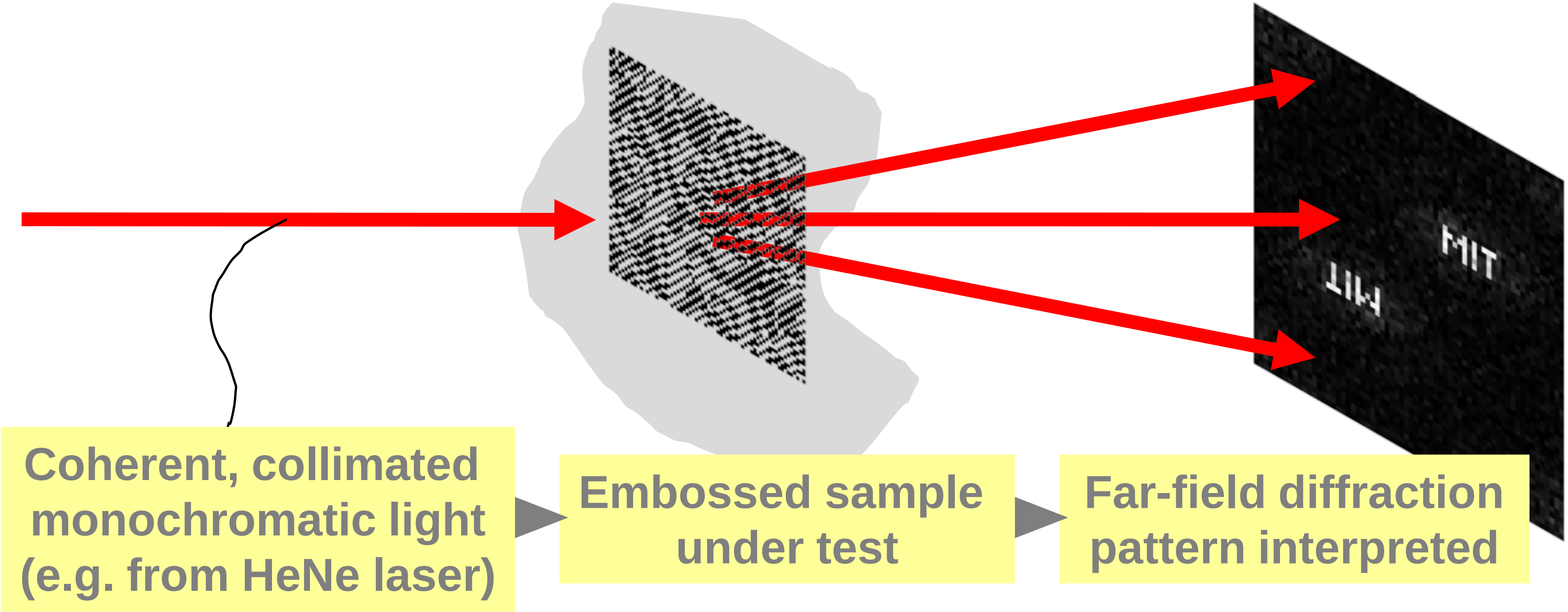
- **Speed: tens of components per minute**
  - alignment required not better than ± 1 mm or ± 1°
- **Non-destructive**
  - ideally non-contact
- **System cost**
  - perhaps ~ $1k (*cf*. embossing systems ~ $100k)
- **Measurement capabilities**
  - lateral dimensions 1 – 500 µm
  - out-of-plane resolution sub-100 nm
  - able to measure buried structures
  - optically transparent materials

Existing approaches

- **Optical methods**
  - interferometry
  - microscopy
- **Scanning probe methods**
- **Scanning electron microscopy**

V. Shilpiekandula, D.J. Burns, K. Youcef-Toumi, K. El Rifai, S. Li, I. Reading, and S.F. Yoon, "Metrology of Microembossed Devices: a Review," in *Proc. Intl Micromanufacturing Conf.,* Sep. 2006, pp. 302–307.

Proposed approach: use Fraunhofer diffraction



Coherent, collimated monochromatic light (e.g. from HeNe laser)

Embossed sample under test

Far-field diffraction pattern interpreted

- **Potential benefits: contact- and alignment-‘free’**
- **Inspired by *scatterometry*, used in semiconductor metrology**

Proposed approach: use Fraunhofer diffraction

- Unlike scatterometry, we have:
  - wavelength << lateral feature dimensions;
  - transmissive substrates;
  - many more diffracted orders produced;
  - plus we require higher measuring speeds

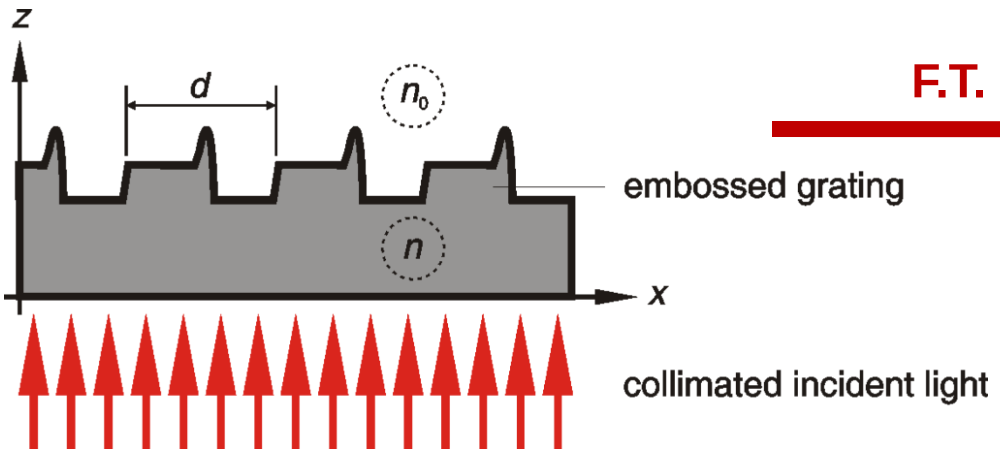
Proposed approach: use Fraunhofer diffraction

- **Far-field amplitudes *B*(*θ*) can be computed as Fourier Transform of component's transmission function**

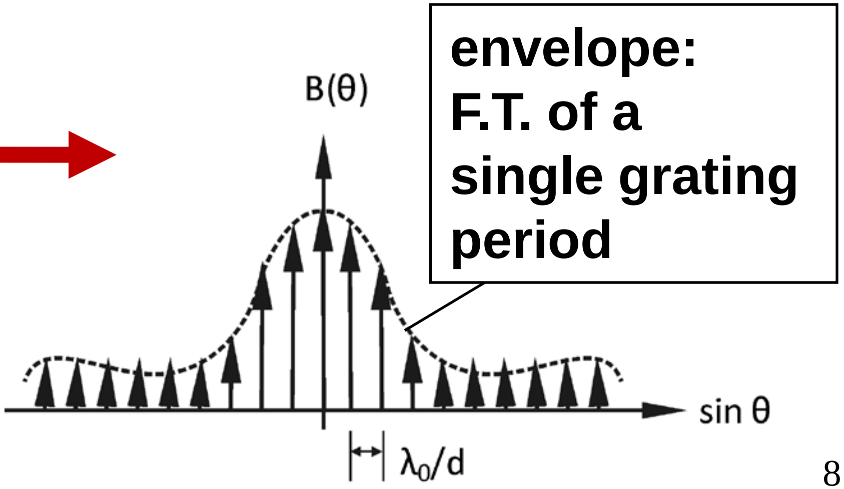
$$\varphi(x) = \frac{2\pi(n_0 - n)}{\lambda_0} z(x)$$

$$B(\theta) = \sum_{k=1}^{S} \exp\left[\frac{2\pi\, jkd \sin\theta}{\lambda_0}\right] \int_0^d \exp\left[-\frac{2\pi\, j x \sin\theta}{\lambda_0} - j\varphi(x)\right] dx$$

For number, S, of grating periods large:



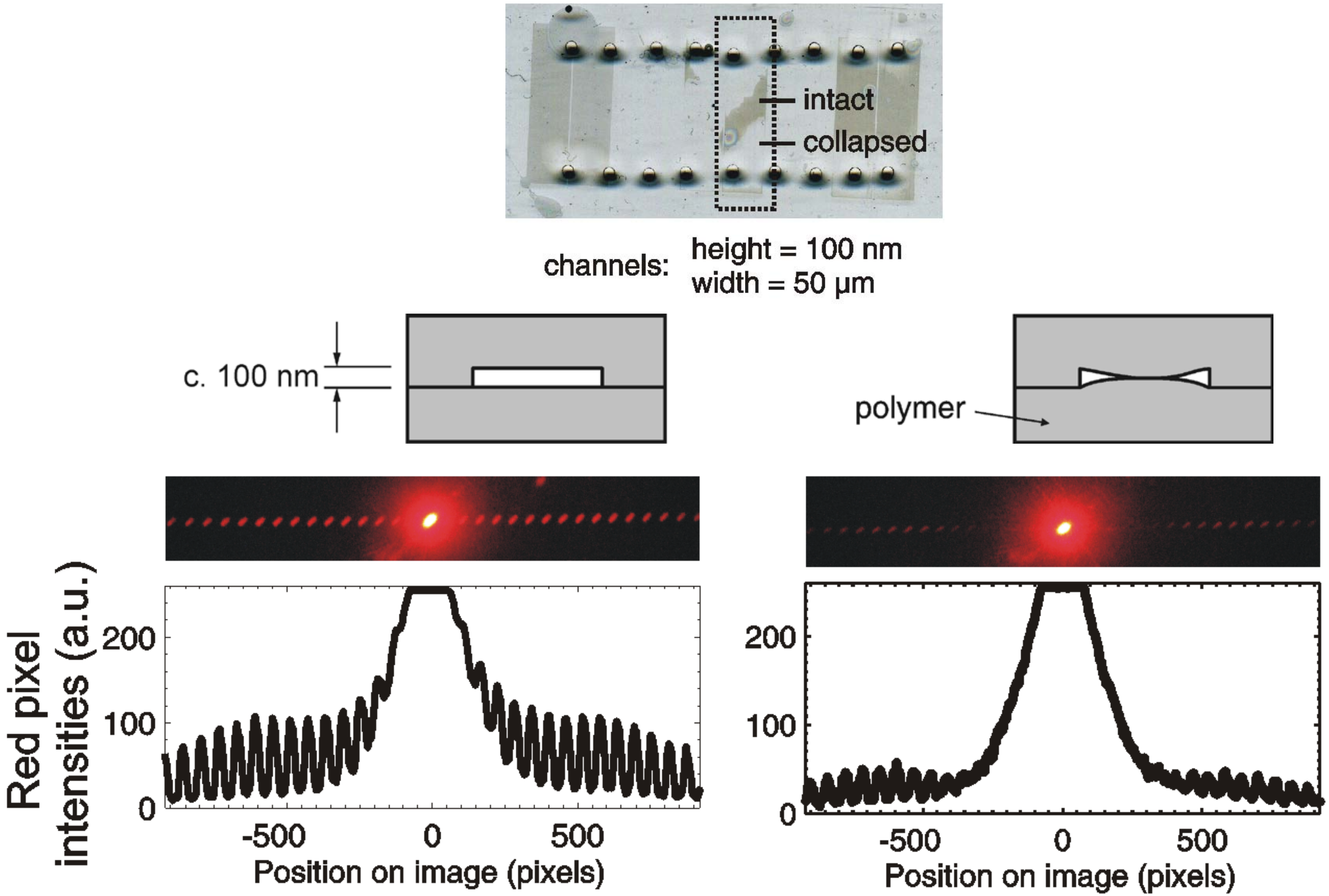
F.T.



envelope: F.T. of a single grating period

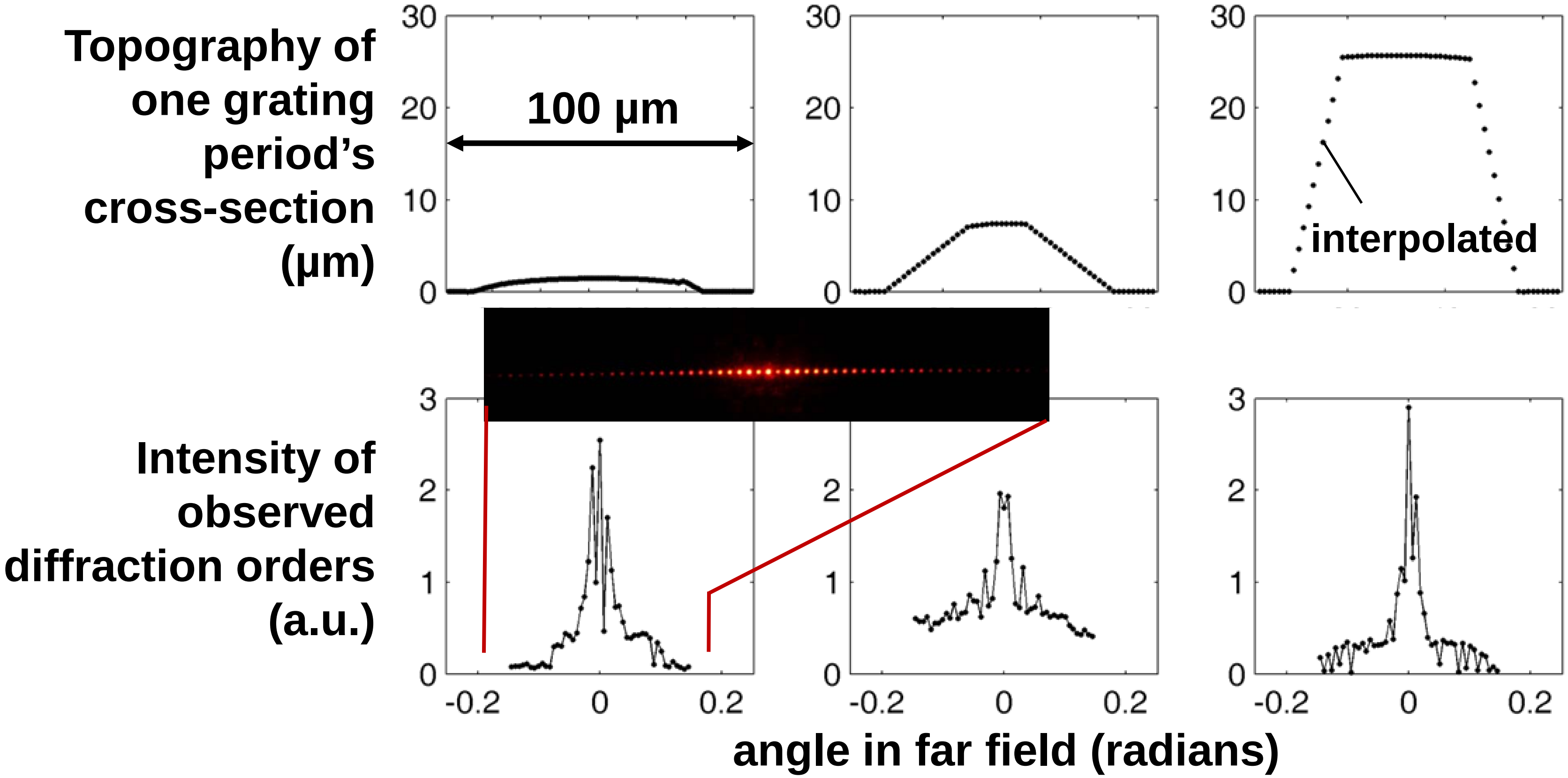
Simplest approach: use regular, 1-D grating

- **Detection of collapsed nanochannels: promising**



Simplest approach: use regular, 1-D grating

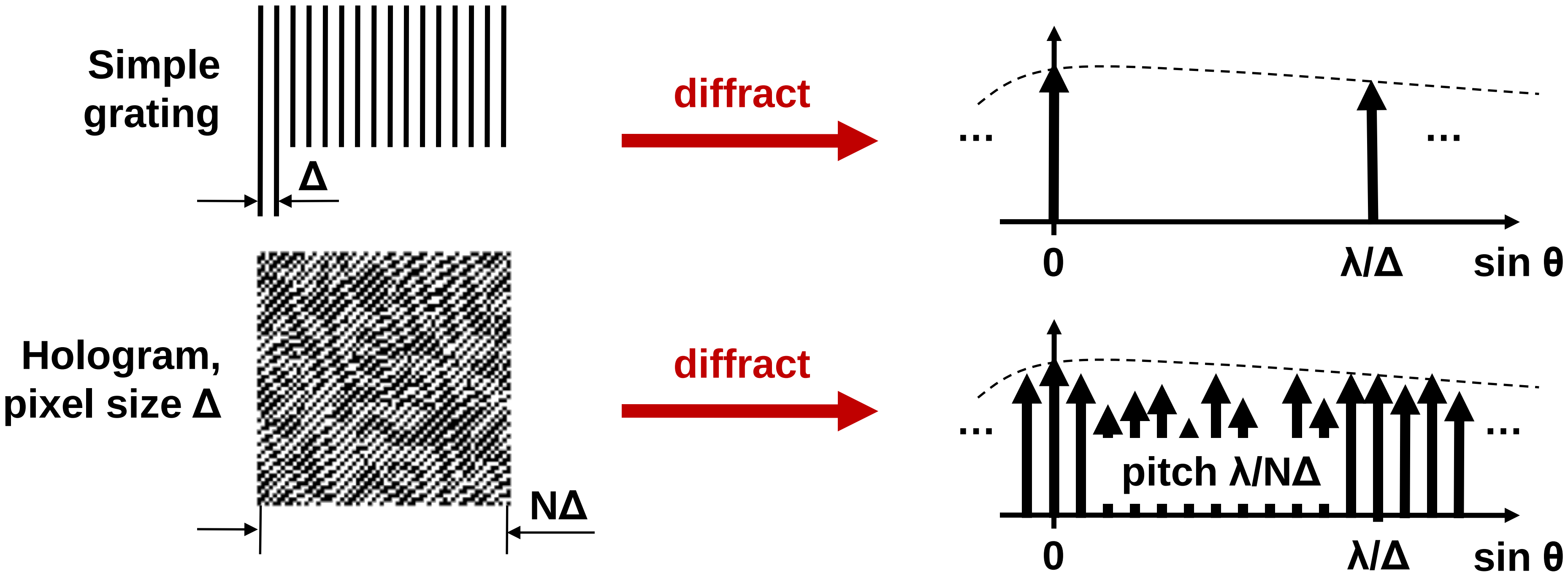
- **Incomplete embossing: changes in topography cause non-intuitive changes in envelope**



- **Irrelevant variations may complicate interpretation**
- **Need a calibrated sensor and controlled environment**

Holographic elements instead of regular gratings?

- **Holograms redistribute energy in far-field, and provide more information within a given angular range.**
- **Could design holograms to reduce interpretation of diffraction patterns to intensity *comparisons* only**
- **Can we design patterns to identify specific defects?**



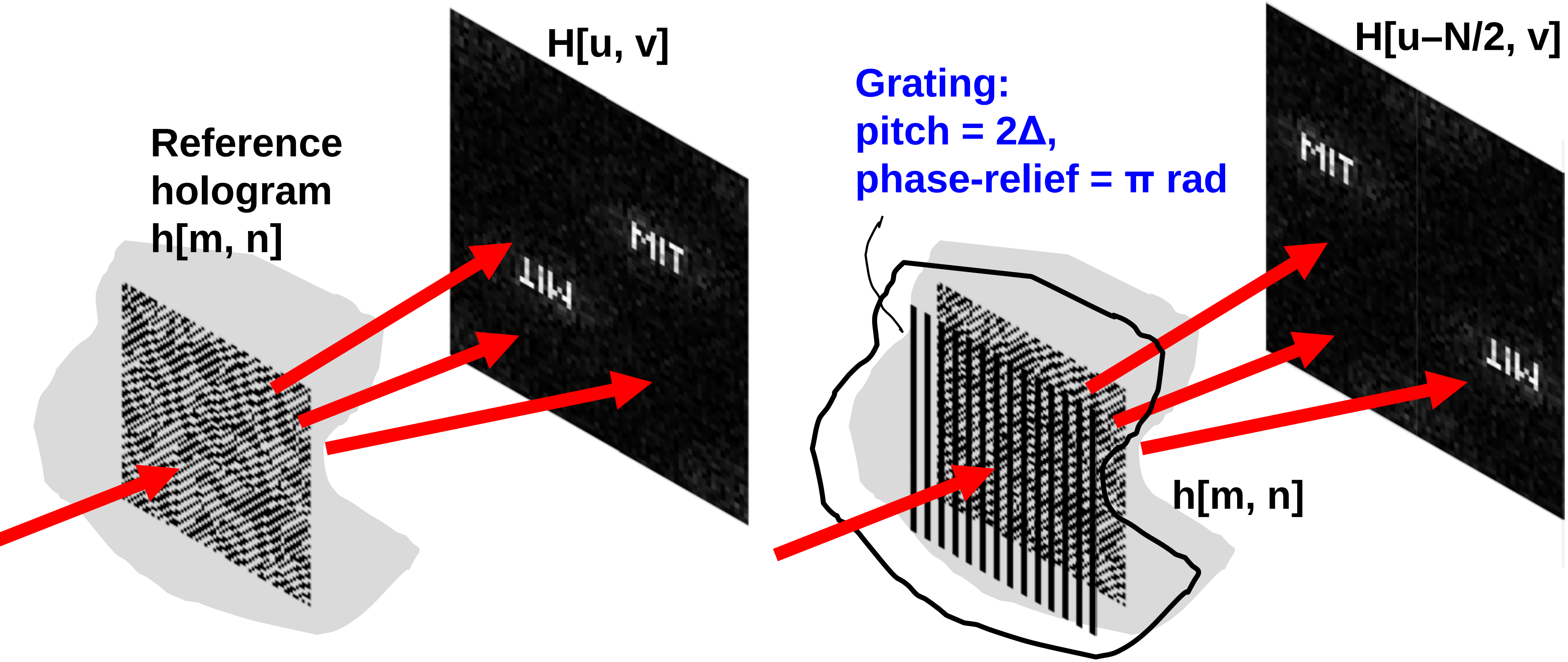
Two approaches using holograms

1. **Reference holograms modulate light passing through a simple part containing an embossed grating**

2. **Hologram built into the part itself**

Idea 1: measuring the depths of nanochannels

- **Quadrant-swapping effect of grating in contact with hologram:**



Reference hologram $h[m, n]$

$H[u, v]$

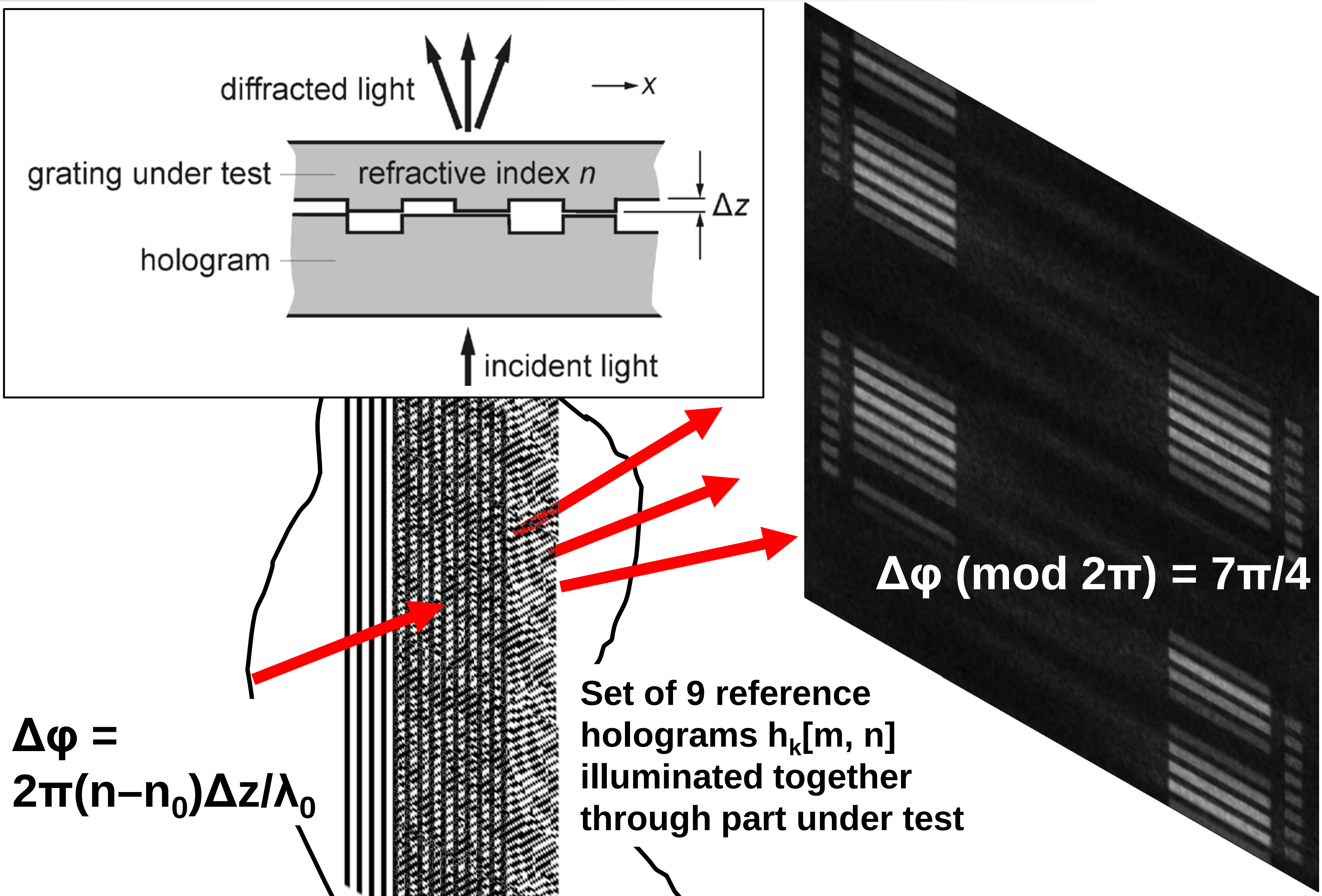
Grating:
pitch = 2Δ,
phase-relief = π rad

$H[u–N/2, v]$

$h[m, n]$

- **Different grating phase-reliefs produce a weighted superposition of these two cases**

Nanochannel depth-measurement scheme

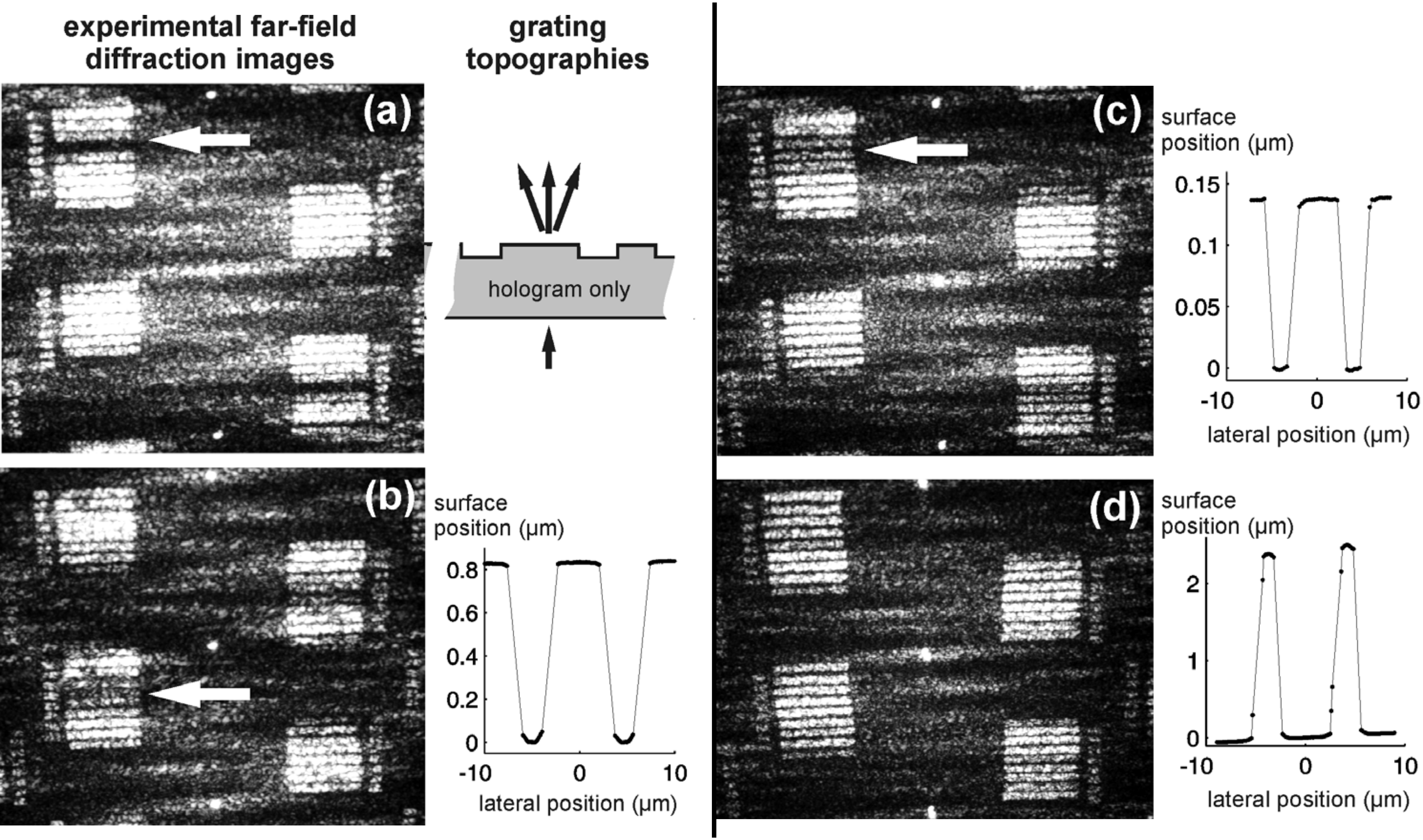


$\Delta\varphi \pmod{2\pi} = 7\pi/4$

$\Delta\varphi = 2\pi(n - n_0)\Delta z/\lambda_0$

Set of 9 reference holograms $h_k[m, n]$ illuminated together through part under test

Nanochannel depth-measurement scheme

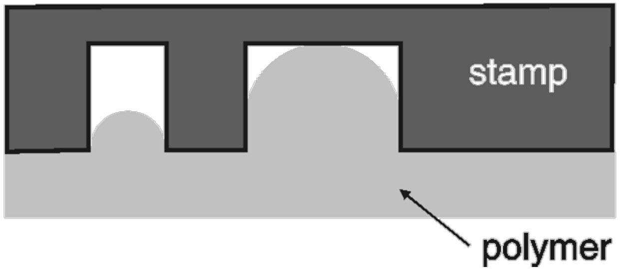


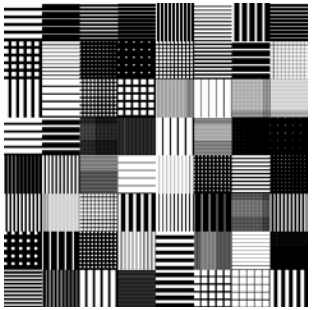
Nanochannel depth-measurement: limitations

- **Resolution for red light and PMMA ~ 200 nm with present hologram designs**
- **Angular alignment sensitivity is severe**
- **Linear offset introduces ambiguity if phase-relief can be greater than π rad.**
- **Requires physical contact between holograms and part under test**
- **Always ambiguous for gratings with a phase-relief of larger than 2π rad; yet we will sometimes need to measure channels that are many λ deep.**

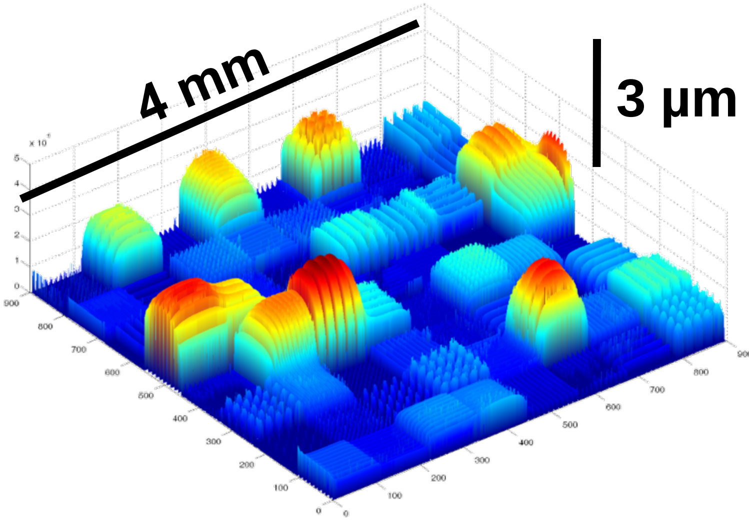
Idea 2: measuring incomplete feature formation

- Narrower features harder to fill than wider, when polymer in a rubbery regime





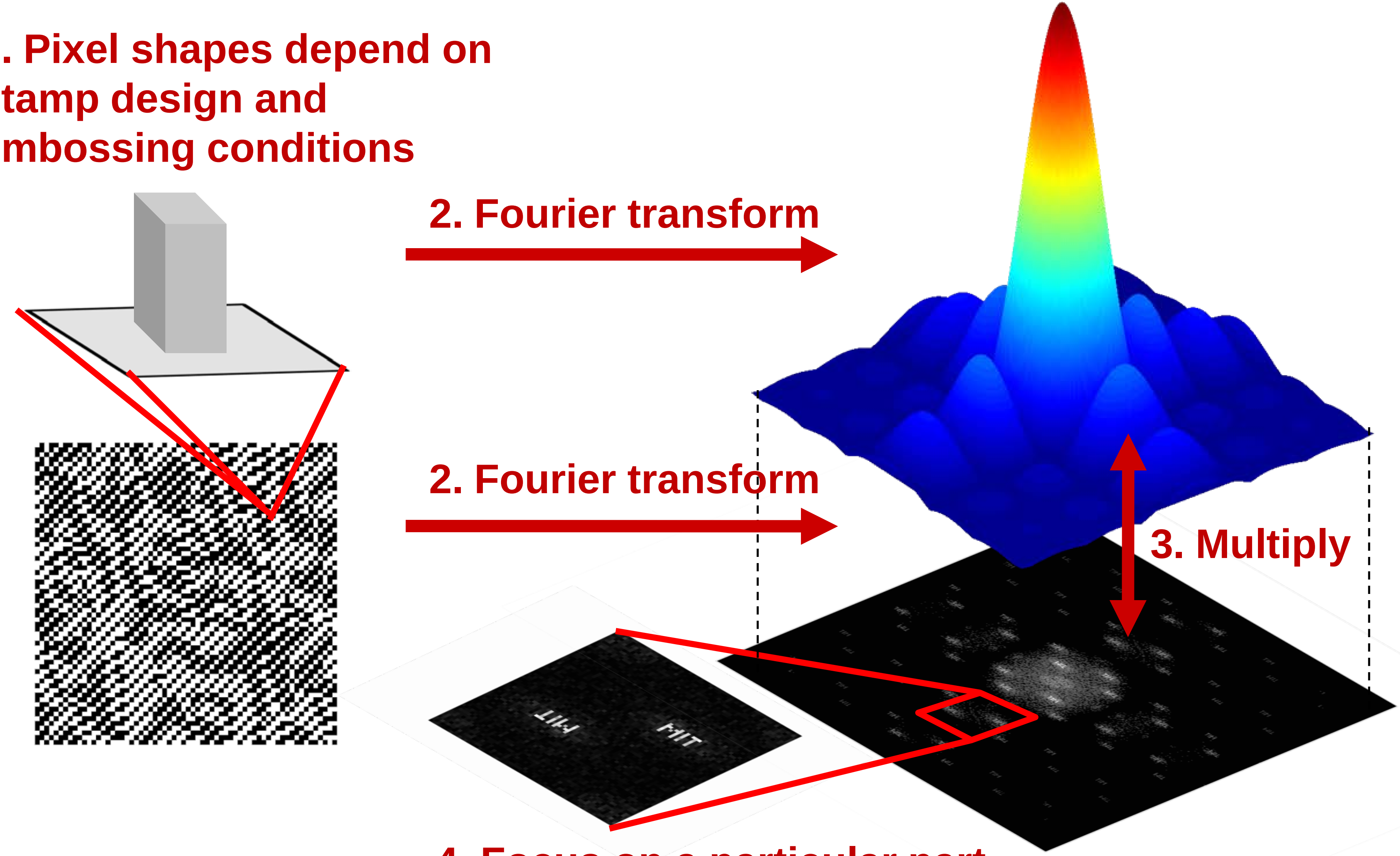
pattern-dependency test stamp



measured topography, PMMA, 110 °C, 8 MPa

- Can exploit this behaviour to detect excessively low embossing pressure

Topography of pixel determines intensity envelope



1. Pixel shapes depend on stamp design and embossing conditions

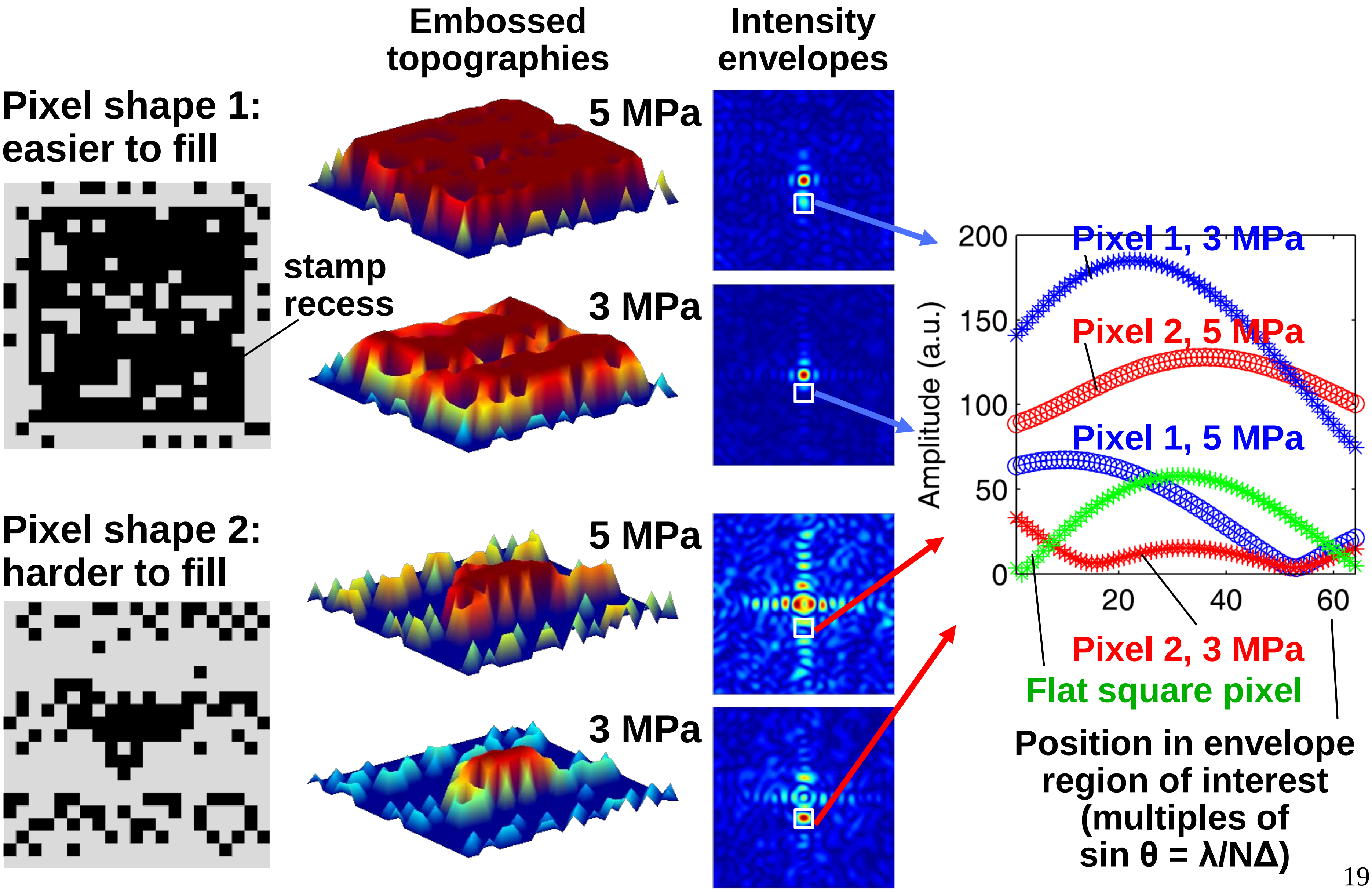
2. Fourier transform

2. Fourier transform

3. Multiply

4. Focus on a particular part of the Fraunhofer plane

Two pixel designs developed to give substantial and opposite changes in envelope intensity



Embossed topographies

Intensity envelopes

Pixel shape 1: easier to fill

stamp recess

5 MPa

3 MPa

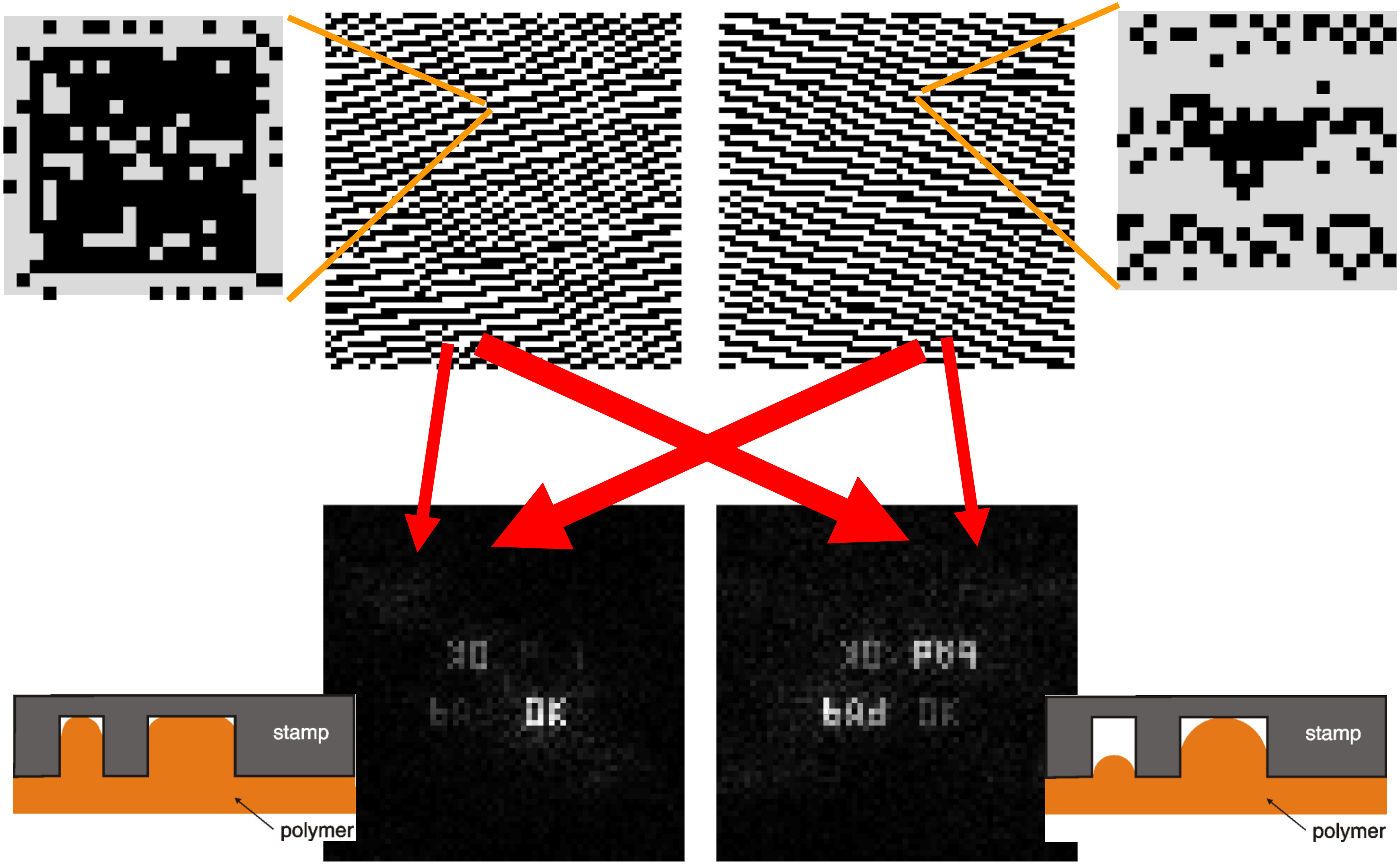
Pixel shape 2: harder to fill

5 MPa

3 MPa

Position in envelope region of interest (multiples of $\sin\theta = \lambda/N\Delta$)

Two holograms and corresponding pixel designs respond to varying embossing pressure



Idea 2: challenges and opportunities

- Requires definition of sub-pixel features: stamp fabrication expensive?
- Could enhance information provided by designing holograms with richer, graded-intensity patterns
- If multi-level stamps are available, could have greater control of pressure-sensitivity

Summary and future directions

- **Overall idea: reduce interpretation of diffraction patterns to a series of ‘binary’ intensity comparisons**
- **Idea 1: nanochannel depth measurement**
  - well defined output
  - requires contact and alignment
- **Idea 2: incomplete filling detection for microchannels**
  - design approach demonstrated
  - uses optimised pixel *and* hologram designs
  - a promising stand-alone metrology tool
  - needs fabricating and testing
  - need to check insensitivity to other processing defects
- **Future directions**
  - layer-layer alignment
  - global distortion check
  - diffractive components in fluidic devices

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