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Technical Groups

An Insight into Holographic Sensors Research: Challenges and Applications

Featuring Izabela Naydenova, Technological University Dublin

25 March 2022

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About Our Technical Group

Our technical group focuses on the design and implementation of holographic and diffractive-optic devices and systems for scientific, commercial, and other applications.

Our mission is to connect the 1000+ members of our community through technical events, webinars, networking events, and social media.

Our past activities have included:

- Digital Holographic Microscopy Techniques for Applications in Cytometry and Histology
- Structured Light with Digital Holograms
- Metasurface Holograms
- Real-Time Hologram Rendering from Optically-Acquired Interferograms

Connect with our Technical Group

Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

Ways to connect with us:

- Our website at www.optica.org/FH
- On LinkedIn at www.linkedin.com/groups/4826728
- On Facebook at www.facebook.com/groups/opticaholography
- Email us at TGactivities@optica.org

Today’s Speaker

Prof. Izabela Naydenova

Technological University Dublin

Izabela Naydenova received her MSc in Applied Optics from the University of Sofia (1993) and PhD in Physics from the Bulgarian Academy of Sciences (1999). Worked as a Postdoctoral researcher at the Technical University of Munich, (1999-2002). Joined the Centre for Industrial and Engineering Optics (IEO), Dublin Institute of Technology as an Arnold F. Graves postdoctoral research fellow (2002-2005), Senior Postdoctoral Researcher (2005-2008) and took up current position as a Lecturer in the School of Physics, DIT in 2008. She was awarded the title of DIT Honorary Professor in 2017. Since 2021 she is the Scientific Director of the IEO. Current research interests are in holographic recording materials and their applications in sensing and fabrication of diffractive optical devices. Prof. Naydenova is co-author of more than 130 papers, 7 book chapters and 6 granted patents. She is co-founder of Optrace Ltd. She has supervised 12 PhD, 5 Master and 45 Bachelor students to their completion.

An Insight into Holographic Sensors Research: Challenges and Applications

Izabela Naydenova

Centre for industrial and Engineering Optics/ School of Physics and Clinical & Optometric Sciences

TU Dublin

OPTICA Webinar, 25th March 2022

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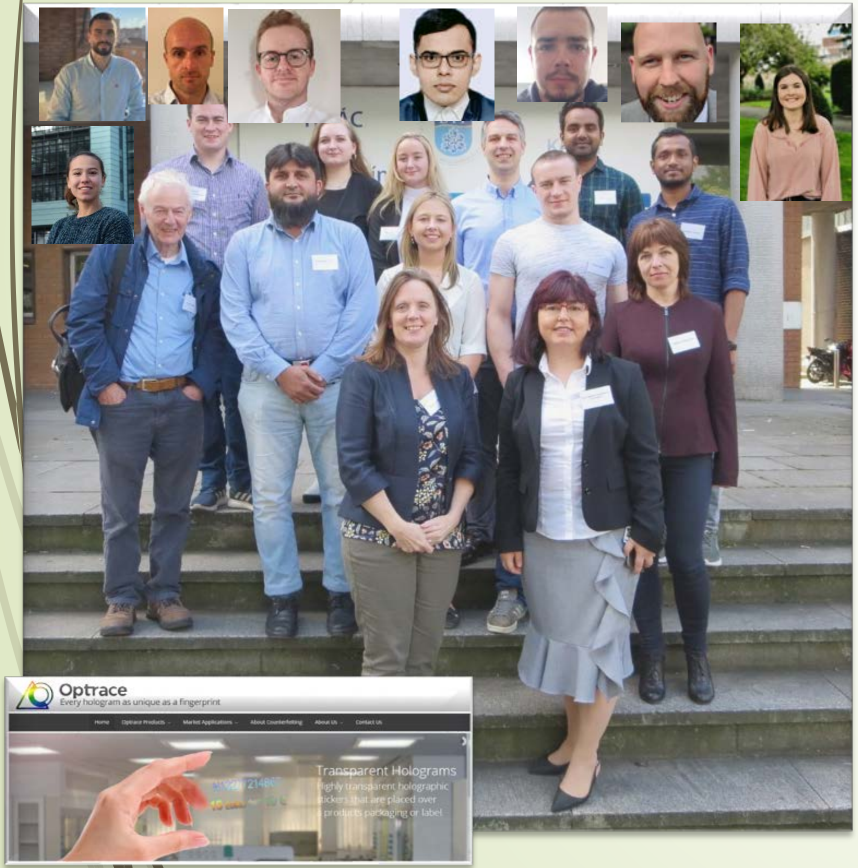


Prof. I Naydenova
Functionalised Optical Structures (Sensing, Security, Micro-actuators)

Dr S. Martin
Holography for Diffractive Optical Elements

Dr K. Murphy
Holography for Wavefront Sensing & Vision

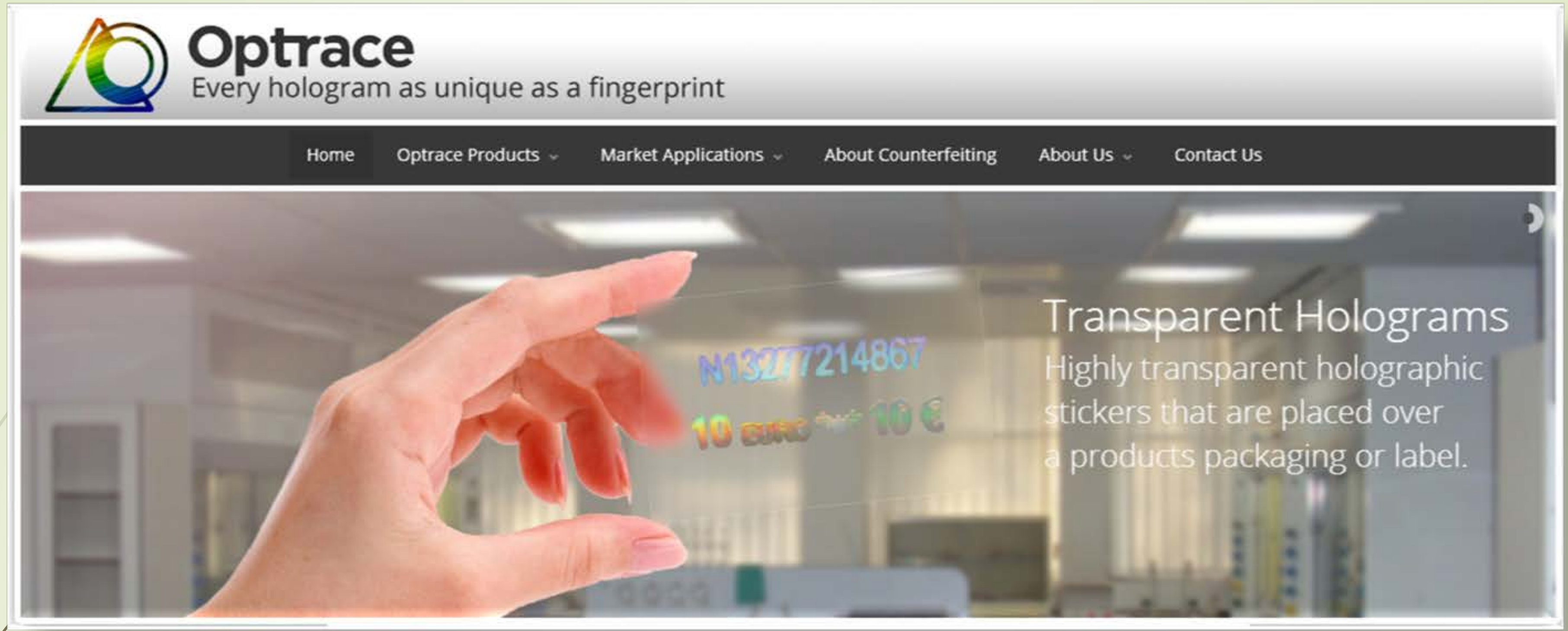
Materials research
Dr Mikulchyk - Sol-gels

Dr D. Cody
Calibration and Quality Assurance of Medical Technologies

Interferometry and Computational Imaging
Prof V. Toal

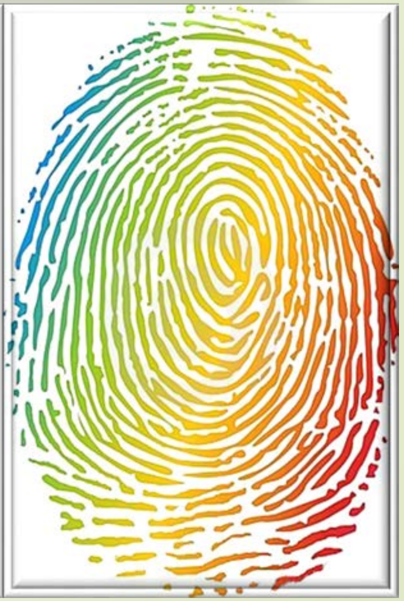
IEO – est. 1998
Publications > 300
Patents granted >10
Postgraduate Students graduated – 36 (PhD 21)
Undergraduate students trained > 160
Spin-out company (2013)

- 4 Full time researchers
- 2 Academic staff
- 11 PhD students
- 2 MPhil students
- 10 undergraduate students



- Spin –out company 2013 - 2021
- Irish based company
- Producers of holographic security labels and equipment for their production

INDIVIDUALISED HOLOGRAMS



Outline

- Holographic sensors principle of operation
- Design and fabrication of holographic sensors
- Temperature sensitive holograms
- Zeolite doped sensors for detection of VOCs
- SRG for detection of heavy metals in water
- Aztec grating for detection of humidity
- Pressure sensor

Holographic sensors: principle of operation, advantages and main challenges

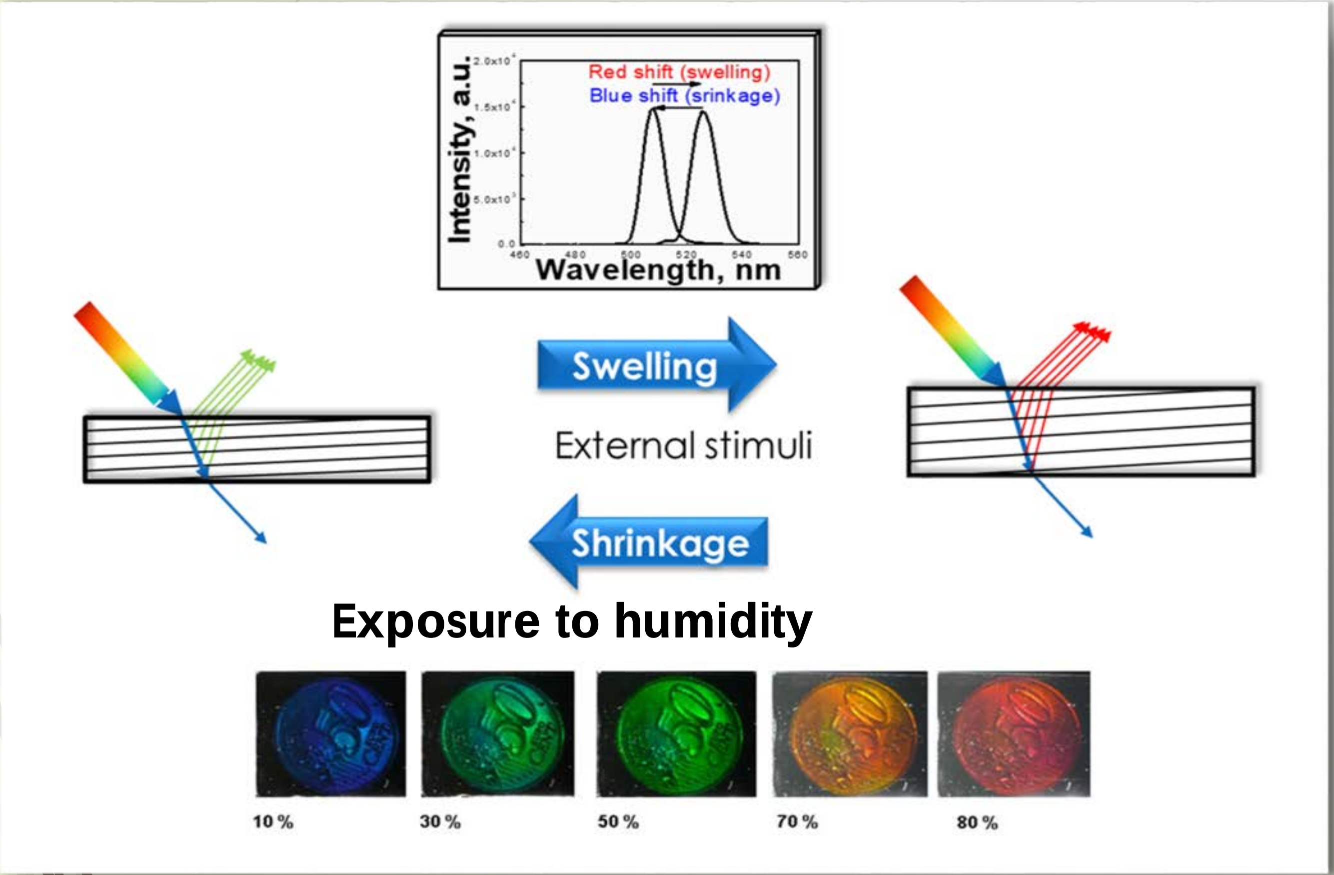
Holographic sensors

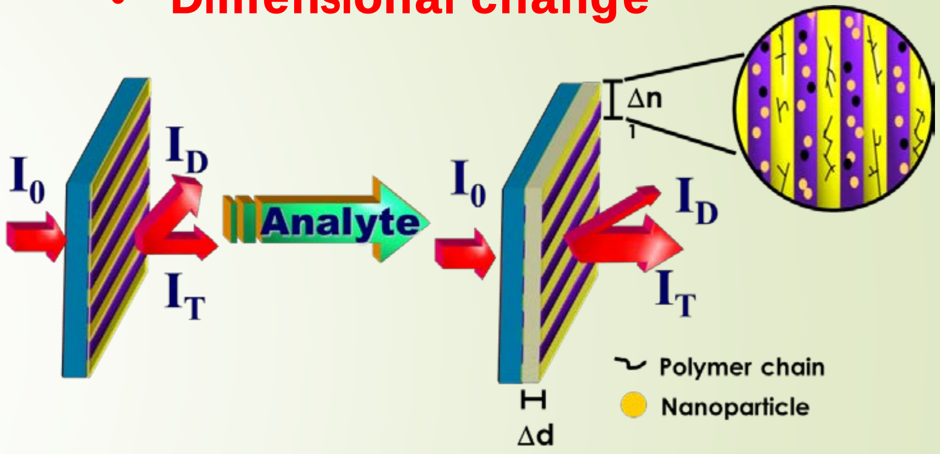
Spatially varying refractive index/thickness

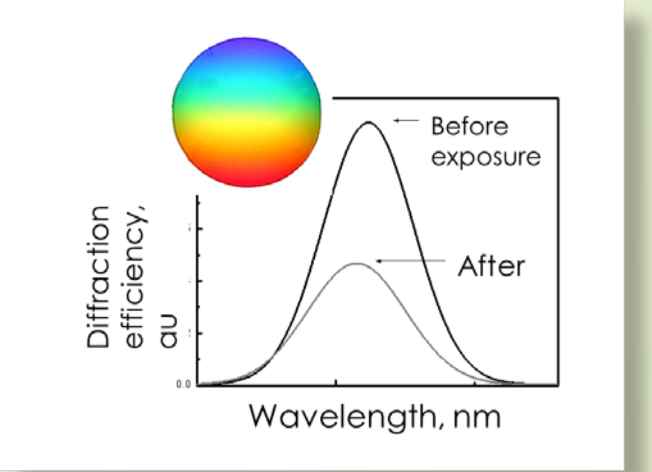
Visual detection – three-dimensional image capability

Compatible with laser manufacturing

- **Effective Refractive index**
- **Refractive index modulation**
- **Dimensional change**







A. K. Yetisen, et al, Chem. Rev. 114, 10654–10696 (2014).

I. Naydenova, “Holographic sensors” in “Optical Holography”, Edited by Pierre-Alexandre Blanche, Elsevier Inc, 2020, ISBN: 978-0-12-815467-0

Response to external stimuli

- Refractive index modulation → Diffraction efficiency
- Dimensional change → Peak wavelength shift; Diffraction efficiency
- Effective Refractive index → Peak wavelength shift; Diffraction efficiency (Bragg angle detuning)

Advantages and Applications

Advantages

- electronic read-out , **remote monitoring**
- visual indication, **no power source required**
- **can be incorporated into packaging**
- **compact size and weight**
- **relatively low cost, disposable**
- **multiplexing** of different sensors is possible

Analytes

Analyte	Dynamic Range	Sensitivity
Trypsin (μg ml^{-1})	< 20	0.04
Water activity in solvents (ppm)	< 20000	120
Alcohols (%)	< 100	0.3
K^+ (mM)	< 30	1
pH	2-9	0.0006
Glucose (mM)	< 375	0.09
Ionic strength (mM)	< 500	0.08
Penicillin G (mM)	< 1-25	0.05
Urea (mM)	< 50	0.15
Ca^{2+} (μM)	<70	2.2
Lactate (mM)	< 12	0.1
Calcium dipicolinate (mM)	> 50	40
Humidity (%, RH)	10-80	1
Edrophonium (μM)	< 300	0.4
Alkanes, alkenes, alkynes (% v/v)	< 100	0.5
Co^{3+} (mmol l^{-1})	< 10	0.01
Organic solvents (%, v/v)	< 10	0.1
Testosterone (μM)	< 10	1.0
Cu^{2+}, Fe^{2+} (1 M)	< 1.0	0.1
Ammonia (NH_3) (%, v/v)	0.19-12.5	2
Pb^{2+}	0.1-10.0 mM	11.4 μM

Yetisen, A. K. ; Volpatti, L. R. ; Humar, M. ; Kwok, S. J. J. ; Pavlichenko, I. ; Kim, K. S. ; Koo, H. ; Butt, H. ; Naydenova, I. ; Khademhosseini, A. ; et al. Photonic Hydrogel Sensors. Biotechnol Adv. 2016 May-Jun;34(3):250-71.

Key challenges in holographic sensors research

- **Selectivity** – novel approaches to functionalisation, sensor arrays
- **Sensitivity**

  novel functionalized photonic structures and materials for holographic recording – functionalized nanoparticles, chemical structure of the copolymerizing monomers, crosslinkers, opto-mechanical structures

- **Visibility**

  optical geometry, type of diffractive optical element (Aztec gratings, diffusers, lenses)

- **Response time**

  host matrix – porosity, hydrophobicity / hydrophilicity, thickness of the device

- **Advantage over existing technologies**

  flexible mass production, easy integration of the sensors with new and emerging technologies - wearable/portable devices and technologies such as microfluidics, potential to be miniaturized in array formats for multiplexing

Holographic Sensors Research

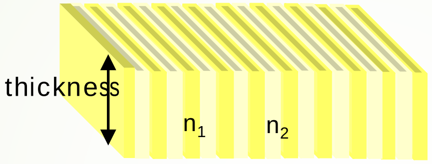
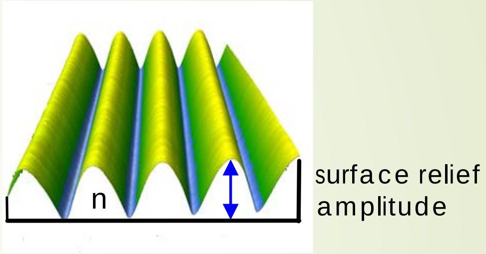
Design of holographic structures

Material development

Functionalisation of the structures

Integration in sensor devices

Selection of the holographic structure

Sensor type	**Holographic sensor based on a volume grating**	**Holographic sensor based on a surface relief grating**
		
Fabrication approach	**Holographic recording in functionalized photopolymers**	**Functionalization of the surface relief grating**
Advantage	**High sensitivity** **Max DE =100%**	• **Faster response time** • **Flexibility in selectivity**
Disadvantage	**Slower response time**	**Lower dynamic range** **Max DE =33%**

Selection of the holographic structure

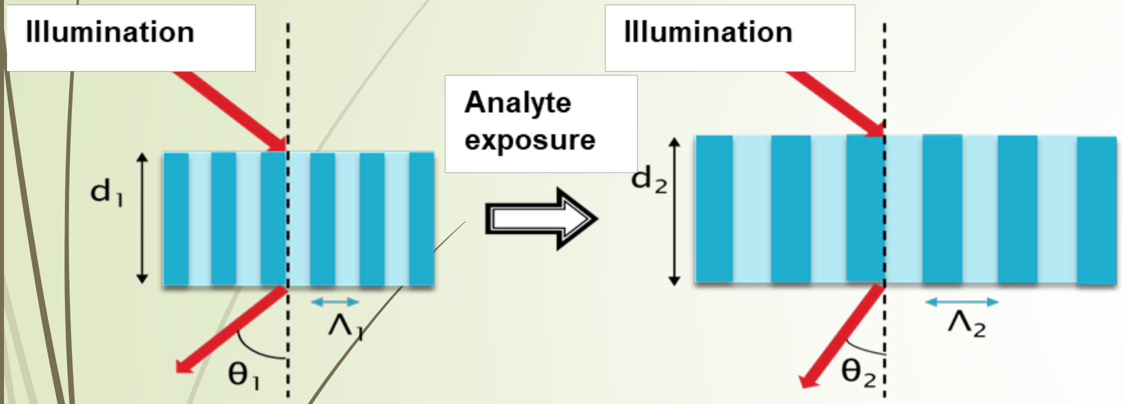
TABLE 7.5
Diffraction Efficiency and Sensitivity of Holographic Sensors.

	Diffraction Efficiency	Sensitivity
Transmission	Thin $\eta = \frac{I_d}{I_o} = J_m^2\left(\frac{\varphi}{2}\right)$	$\frac{\partial(\eta)}{\partial(\Delta n)} = \frac{\pi d}{\lambda_p \cos\theta_B} J_1\left(\frac{\pi d}{\lambda_p \cos\theta_B}\Delta n\right)\left[J_0\left(\frac{\pi d}{\lambda_p \cos\theta_B}\Delta n\right) - J_2\left(\frac{\pi d}{\lambda_p \cos\theta_B}\Delta n\right)\right]$
$m\lambda_p = \Lambda \sin\theta_B$	$\varphi = \frac{2\pi\Delta n d}{\lambda_p \cos\theta_B}$	$\frac{\partial(\eta)}{\partial(\Delta d)} = \frac{\pi\Delta n}{\lambda_p \cos\theta_B} J_1\left(\frac{\pi\Delta n}{\lambda_p \cos\theta_B} d\right)\left[J_0\left(\frac{\pi\Delta n}{\lambda_p \cos\theta_B} d\right) - J_2\left(\frac{\pi\Delta n}{\lambda_p \cos\theta_B} d\right)\right]$
$\lambda_p = 2n\Lambda \sin\theta_B$	Thick $\eta = \sin^2\left(\frac{\varphi}{2}\right)$	$\frac{\partial(\eta)}{\partial(\Delta n)} = \frac{\pi d}{\lambda_p \cos\theta_B}\left[\sin\left(2\frac{\pi\Delta n d}{\lambda_p \cos\theta_B}\right)\right]$
	$\varphi = \frac{2\pi\Delta n d}{\lambda_p \cos\theta_B}$	$\frac{\partial(\eta)}{\partial(\Delta d)} = \frac{\pi\Delta n}{\lambda_p \cos\theta_B}\left[\sin\left(2\frac{\pi\Delta n d}{\lambda_p \cos\theta_B}\right)\right]$
Reflection $\lambda_p = 2n\Lambda \sin\theta_B$	$\eta = \tanh^2\left(\frac{\varphi}{2}\right)$	$\frac{\partial(\lambda_p)}{\partial(\Delta n)} = \frac{\pi d}{\tanh^{-1}(\sqrt{n})\cos\theta_B}$
	$\eta = \tanh^2\left(\frac{\pi\Delta n d}{\lambda_r \cos\theta_B}\right)$	$\frac{\partial(\lambda_p)}{\partial(d)} = \frac{\pi\Delta n}{\tanh^{-1}(\sqrt{n})\cos\theta_B}$

Cody et al, Vol. 35, No. 1 / January 2018 / JOSA A, https://doi.org/10.1364/JOSAA.35.000012

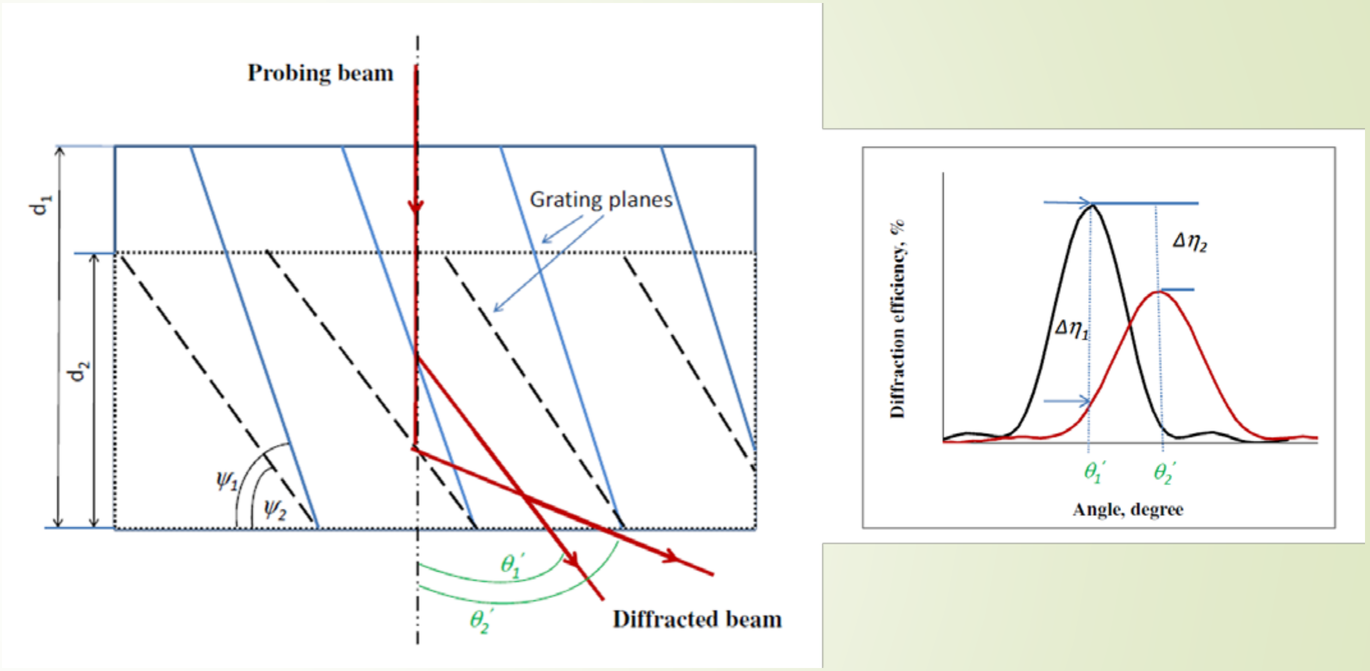
Holographic sensors based on transmission VHG

Unslanted grating



$$\frac{\partial \eta}{\partial d} \quad \frac{\partial \eta}{\partial (n_1)} \quad \frac{\partial \eta}{\partial (\theta_B)}$$

Slanted grating



$$\frac{\partial \eta}{\partial d} \quad \frac{\partial \eta}{\partial (n_1)} \quad \frac{\partial \eta}{\partial (\theta_B)} \quad \frac{\partial \eta}{\partial (\Psi)}$$

Holographic sensors based on transmission VHG

$$\eta = \sin^2\left(\frac{\varphi}{2}\right) \qquad \varphi = \frac{2\pi\Delta n d}{\lambda_p \cos\theta_B} \qquad Q = \frac{2\pi\lambda d}{n\Lambda^2} \qquad Q>10$$

Thickness and Probe Wavelength

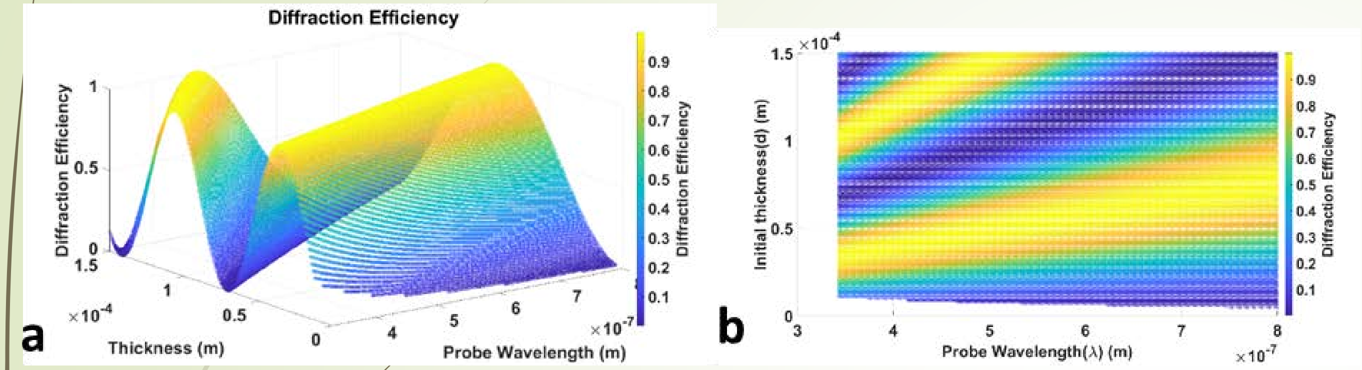


Figure: (a)Variation of the diffraction efficiency of volume transmission gratings with a range of grating thicknesses and probe wavelengths; (b) bird's eye view of (a).

Minimum thickness requirements for volume hologram at different probe wavelength (SF 800 line/mm)

Wavelength (λ_p) (nm)	Grating thickness (d)
380	5um
532	7um
750	10um

Thickness and Spatial Frequency

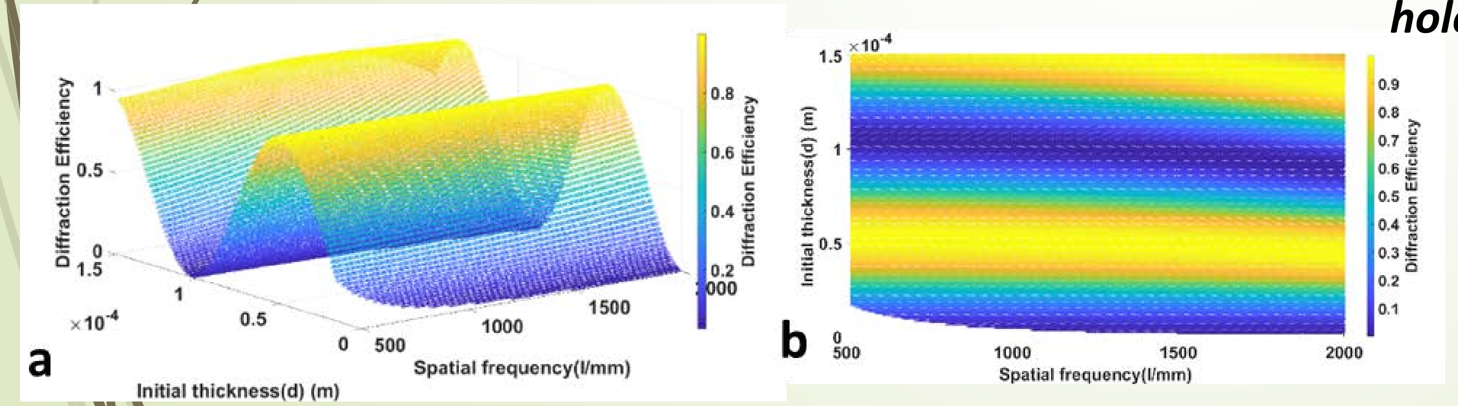


Figure:(a) Variation of the diffraction efficiency of volume transmission grating with gratings thickness and Spatial Frequency. (b) bird's eye view of figure (a).

Minimum thickness requirements for volume hologram at each probe Spatial Frequency λp= 532nm)

Spatial frequency (1/Λ)	Grating thickness (d)
515 l/mm	17um
800 l/mm	7um
1500 l/mm	2um

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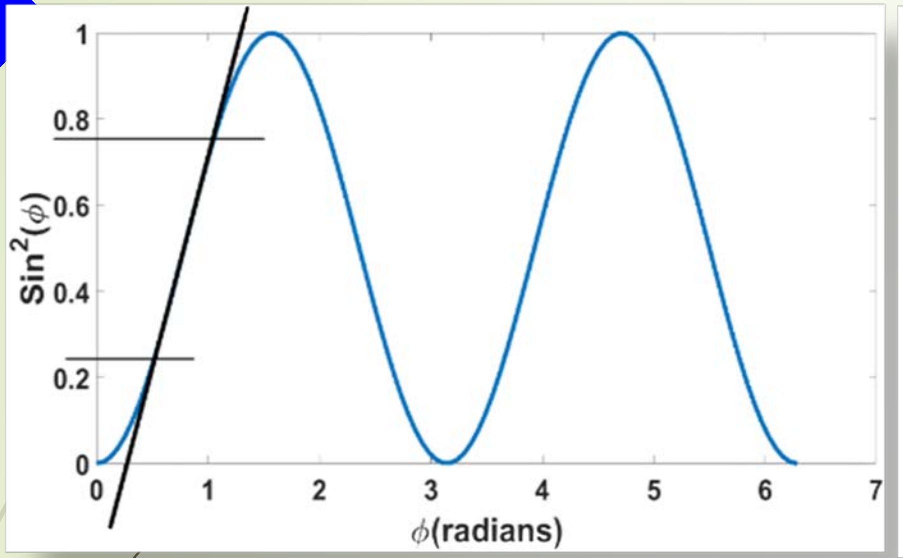
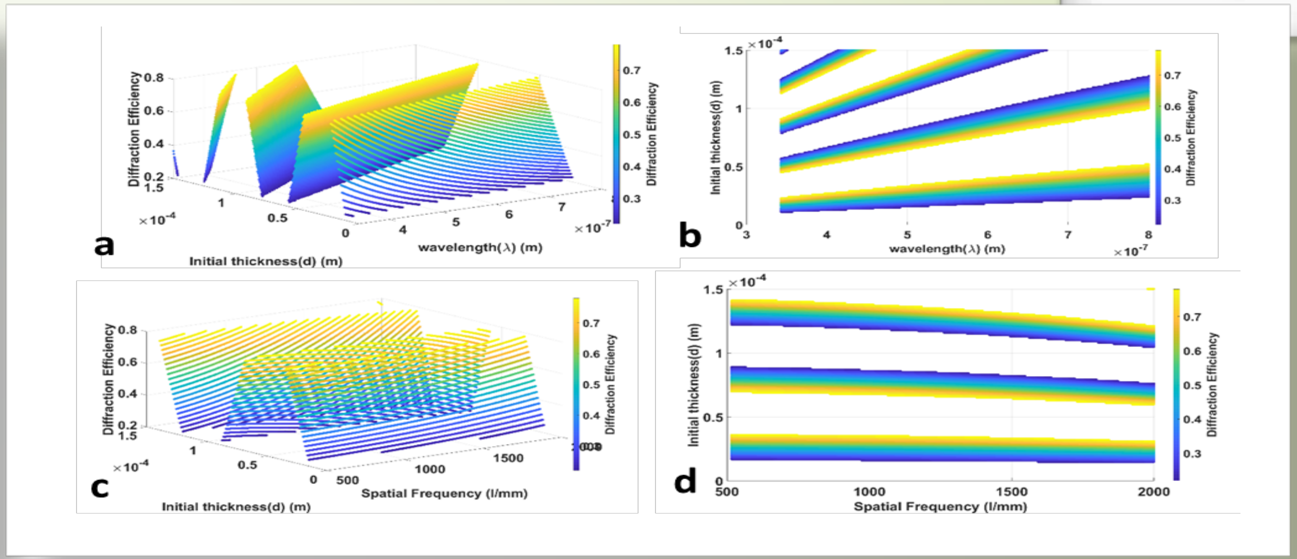
Holographic sensors based on transmission VHG

Linear regime of operation

ieo
Industrial & Engineering Optics





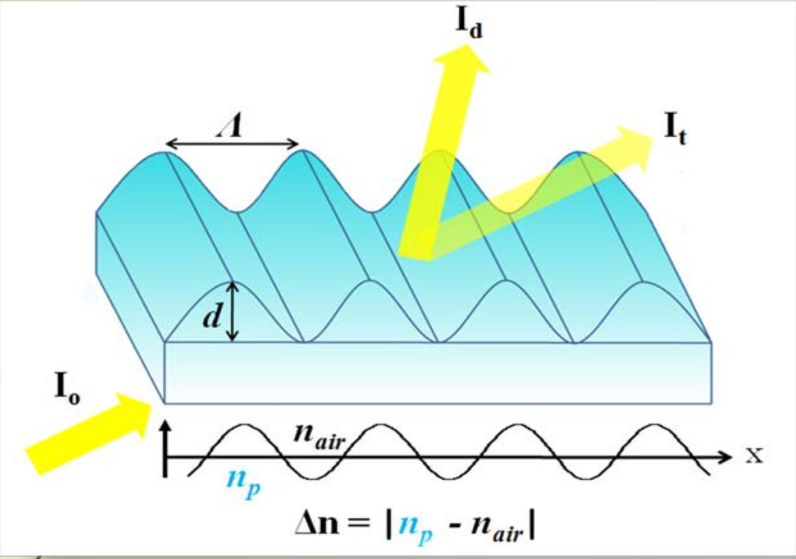
The thickness limits for **linear regime** for different wavelengths (SF=800 lines/mm)

Wavelength (λ_p)	Grating thickness (d) For the lower limit of the linear regime (0.22)	Grating thickness (d) For an upper limit of the linear regime (0.78)
380nm	12um	26um
532nm	17um	35um
750nm	23um	50um

The thickness limits for **linear regime** for gratings of different Spatial frequency (wavelength 633nm)

Spatial Frequency($1/\Lambda$)	Grating thickness (d) For the lower limit of the linear regime (0.22)	Grating thickness (d) For the upper limit of the linear regime (0.78)
515 l/mm	17um	36um
800 l/mm	17um	35um
1000 l/mm	16um	35um
1500 l/mm	16um	33um
2000 l/mm	15 um	31um

Holographic sensors based on surface holograms



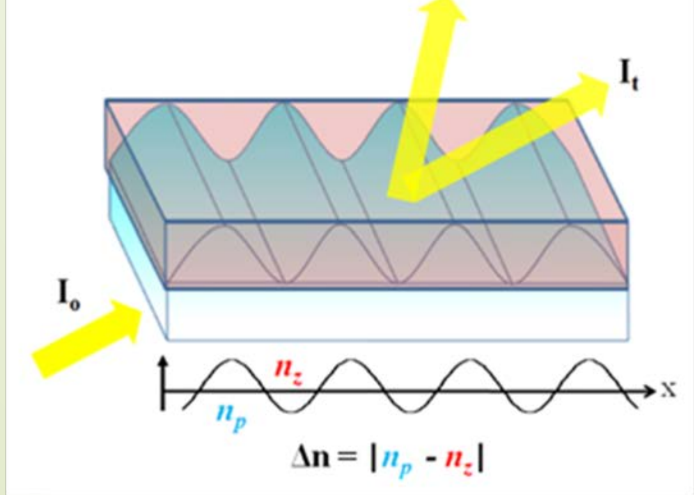
Grating is considered plane when: $Q = \frac{2\pi\lambda_r d}{n\Lambda^2} < 1$

Diffraction Efficiency η of thin grating:

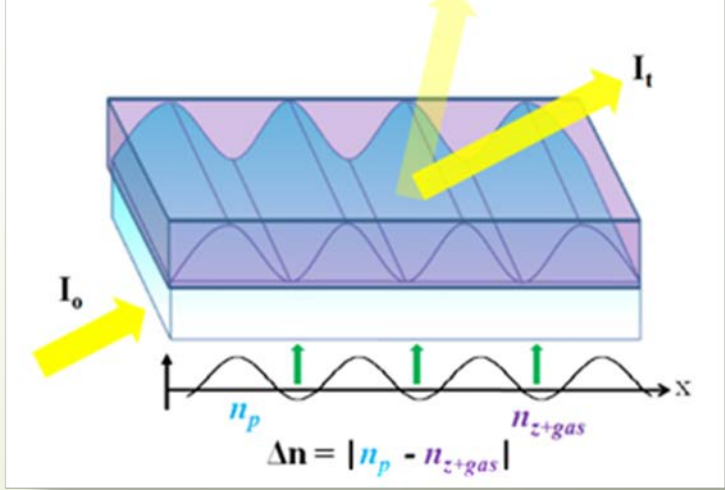
$$\eta = J_m^2\left(\frac{\Delta\varphi}{2}\right) = \frac{I_d}{I_o}$$

where: $\Delta\varphi = \frac{2\pi\Delta n d}{\lambda_r \cos\theta_B}$

Before analyte exposure:

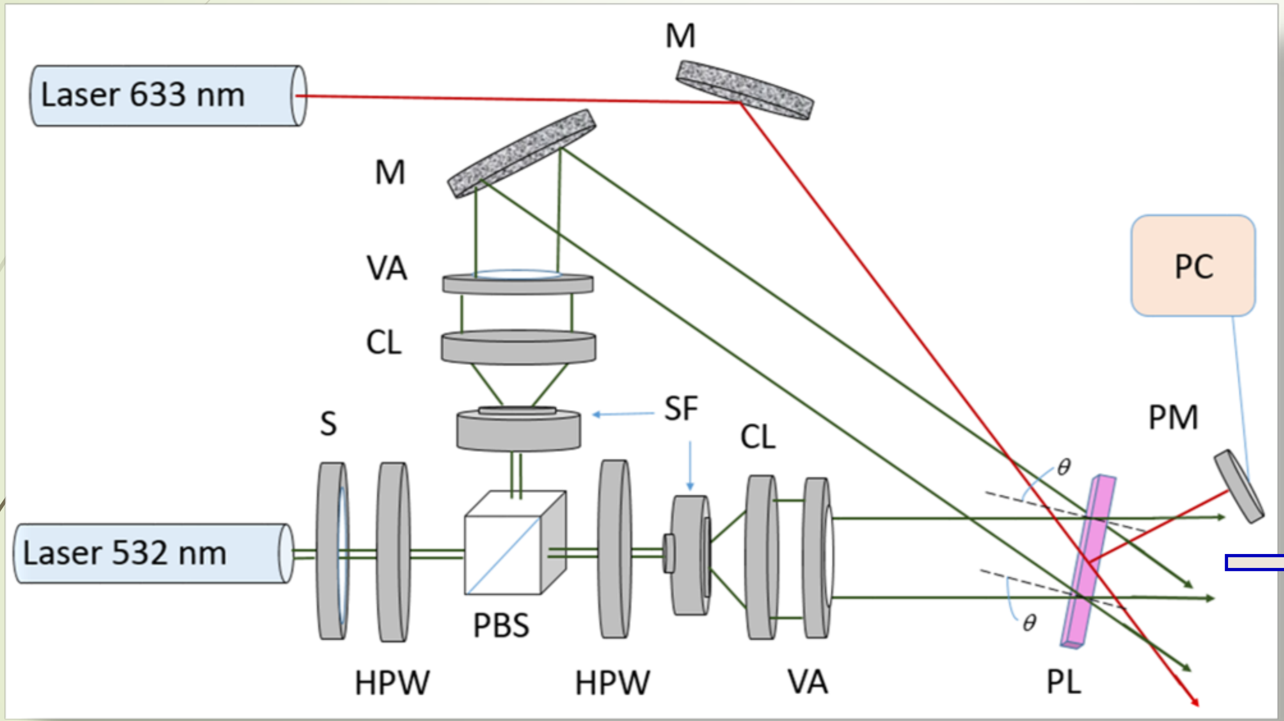


After analyte exposure:



Fabrication: transmission holograms

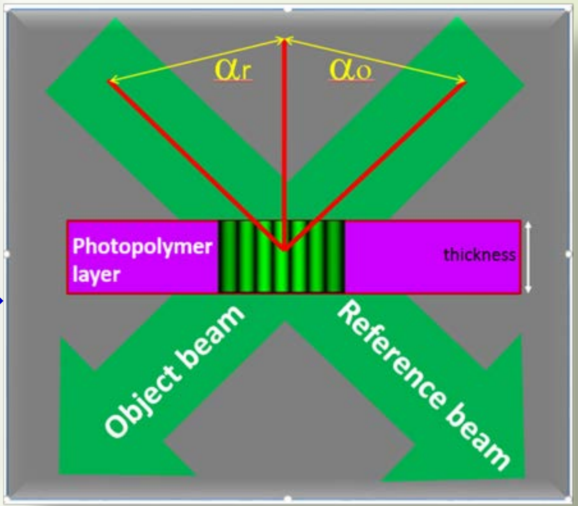
Transmission mode



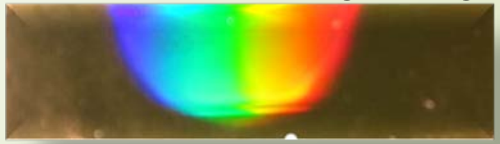
S – electronic shutter; HWP – half-wave plate; PBS – polarizing beam splitter; SF – spatial filter; CL – collimator; VA – variable aperture; M – mirror; PM – power meter; PL – photopolymer layer; PC – computer.

Photopolymer layer

Holographic



Transmission grating

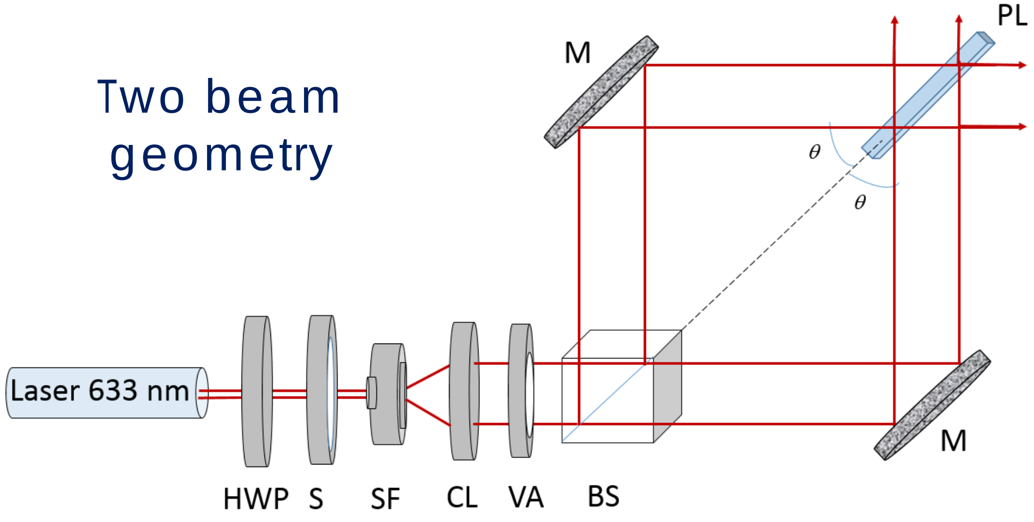


Under white light illumination

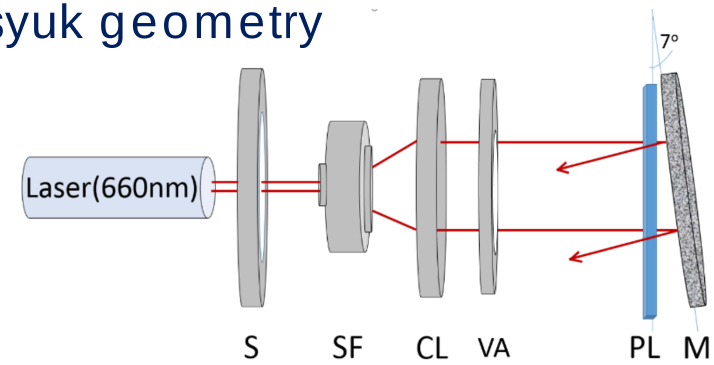
Fabrication: reflection holograms

Reflection mode

Two beam geometry



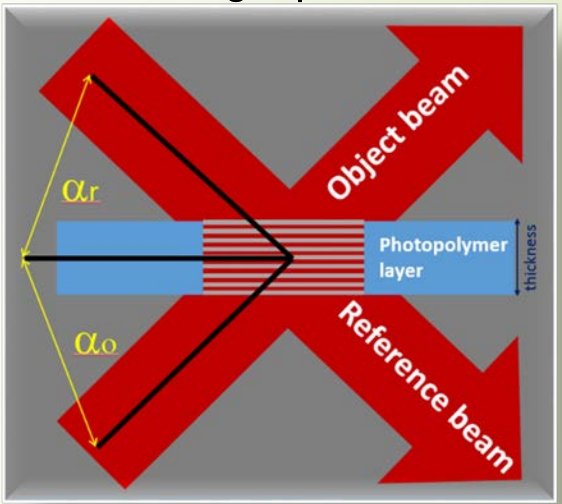
Denisyuk geometry



HWP – half-wave plate; S – electronic shutter; SF – spatial filter; CL – collimator; VA – variable aperture; BS – non-polarizing beam splitter; M – mirror; PL – photopolymer layer.

Photopolymer layer

Holographic



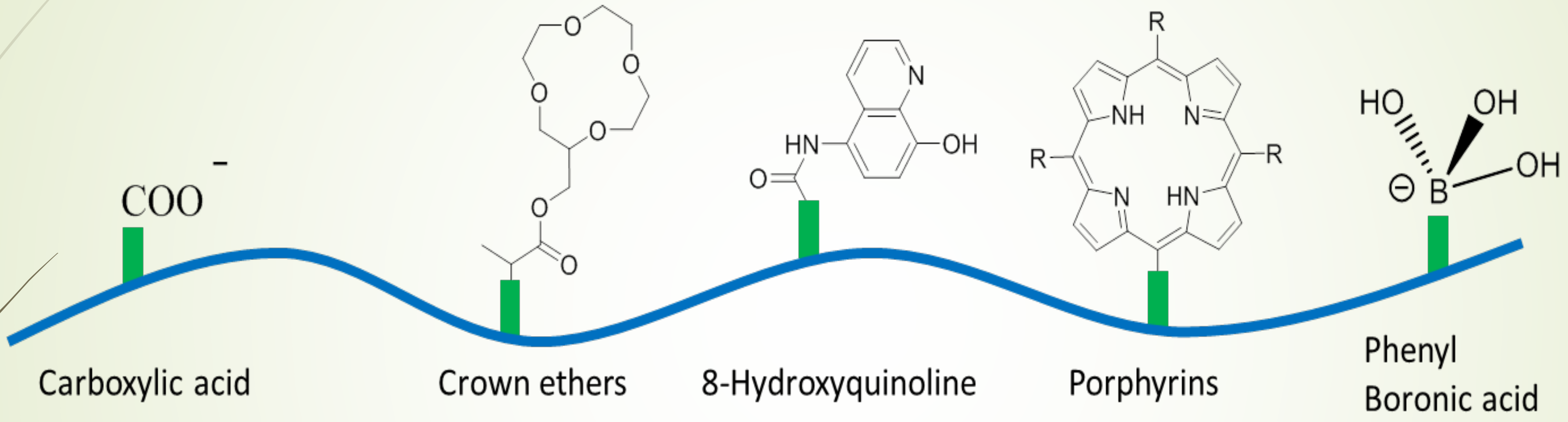
Reflection grating

Under white light illumination

Materials

Materials	Toxicity of the layer	Environmental stability	High optical quality layers, thickness photosensitivity	Capable of holographic recording	Functionalised	Cost - effective	Mass-manufactured
Photopolymer based on hydrogels	Non-toxic	Sensitive to Humidity and/or Temperature (>15 % RH and >30 °C)	30-250 μm	5×10^{-3}	Zeolites, magnetic nanoparticles, calixarenes, crown-ethers, Poly-NIPA, Diacetone-acrylamide	Yes	Yes
Sol-gel materials	Non-toxic	Very stable 1000 hours in water Up to 125 °C	20-200 μm	3×10^{-3} (CW) 9×10^{-3} (2PP)	Zeolite nanoparticles	Yes	No
Cellulose-based recording materials	Non-toxic	Stable 60 min in water	50-100 μm	2.5×10^{-3}	4-tert-butylcalix[4]arene (TBC) ionophores	Yes	No

Functionalisation of holographic sensors by incorporation of various monomers



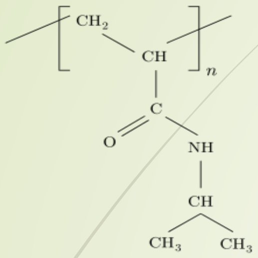
Capability of recording holograms of the functionalised material has to be retained!

Main mechanism- swelling /shrinking of the layer containing the hologram.

Temperature sensor
based on volume gratings

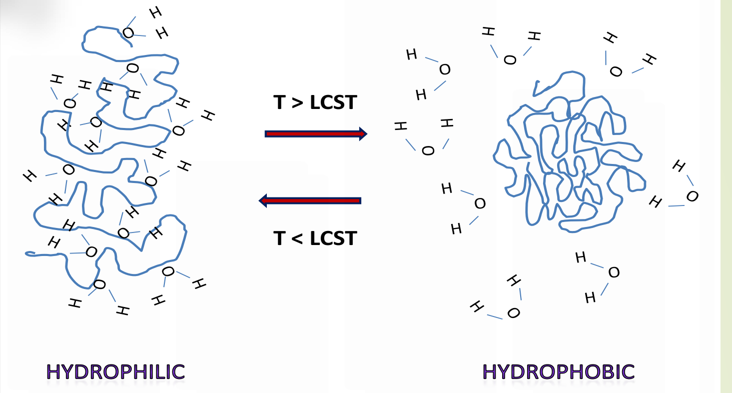
Temperature sensitive photopolymer

(Dr. T. Mikulchyk)



Poly(N-isopropylacrylamide) characteristics:

- ***Lower Critical Solution Temperature (32 °C) : a sharp coil-globule transition***
- ***LCST: hydrophilic state hydrophobic state.***
- ***Reversible changes in microstructure.***
- ***Low toxicity.***

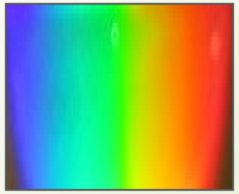


Photopolymer component/ Functionality	*Target*
Polyvinyl alcohol /polymer binder	Solid layer
N-isopropyl acrylamide / monomer	create sensitivity to temperature
N, N'-methylene bisacrylamide / cross-linker	Stability of the recorded structure
N-phenylglycine / electron donor	improved scratch resistance of the layer decreased sensitivity to humidity
Glycerol / plasticizer	improved stability of the phonic structure, improved exposure sensitivity
Citric acid / chain transfer agent	further improvement of the spatial resolution (reflection mode)
Erythrosin B or Methylene Blue /sensitizer	Sensitivity to a specific wavelenghth

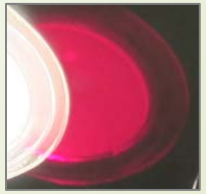
Holographic recording characteristics

- Spatial resolution up to 5600 lines/mm;
- Diffraction efficiency:
Transmission - 80 %;
Reflection – 20 %;
- Refractive index modulation:
Transmission – 4.5×10^{-3};
Reflection – 1.7×10^{-3}.

Transmission



Reflection



Mikulchyk T, Martin S, Naydenova I. 2017. *Applied Optics* **56.**

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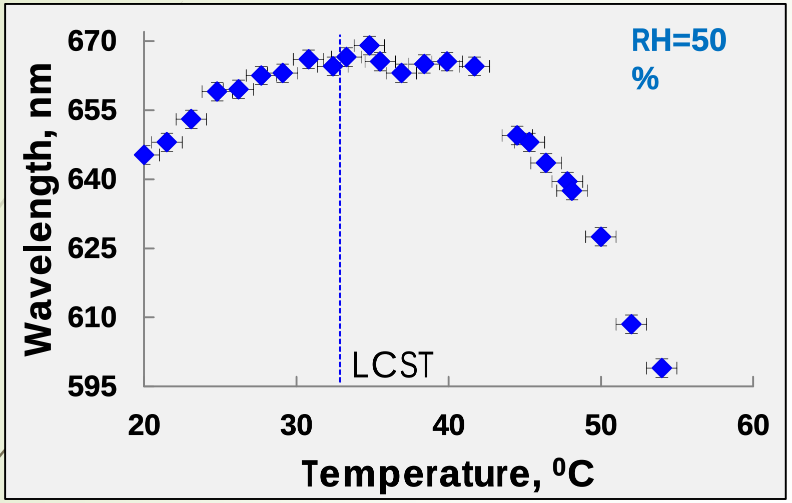
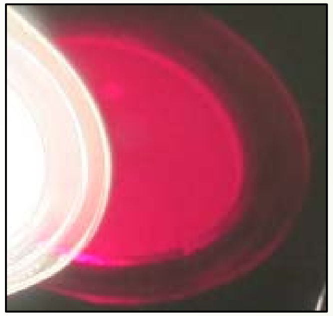
Temperature indicator

volume reflection slanted gratings recorded in NIPA-based photopolymer

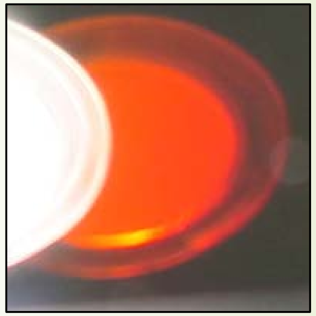
1) Reflection grating (2700 lines/mm)



T = 20 ⁰C

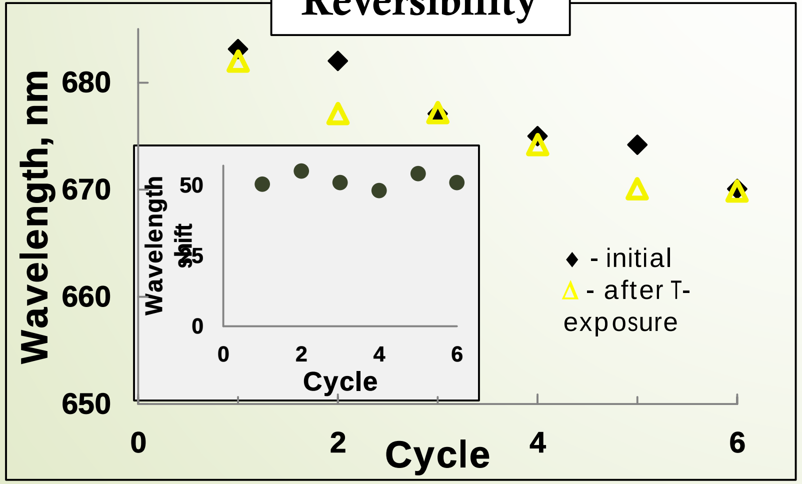


T = 55 ⁰C



60 μm thickness

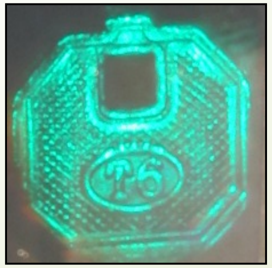
Reversibility



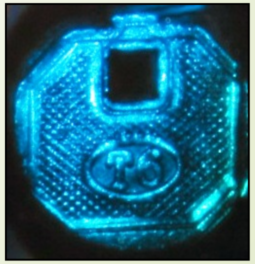
Denisyuk hologram (5600 lines/mm)

temperature indicator

T = 20 ⁰C

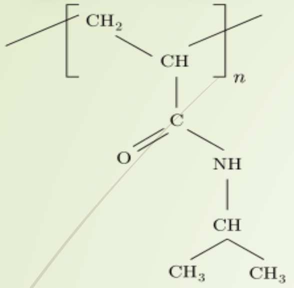


T = 55 ⁰C



Mikulchyk et al, Vol. 56, No. 22 / August 1 2017 / Applied Optics, https://doi.org/10.1364/AO.56.006348

Temperature sensor/indicator
(Dr Tatsiana Mikulchyk and Irfan Muhammad PhD student)

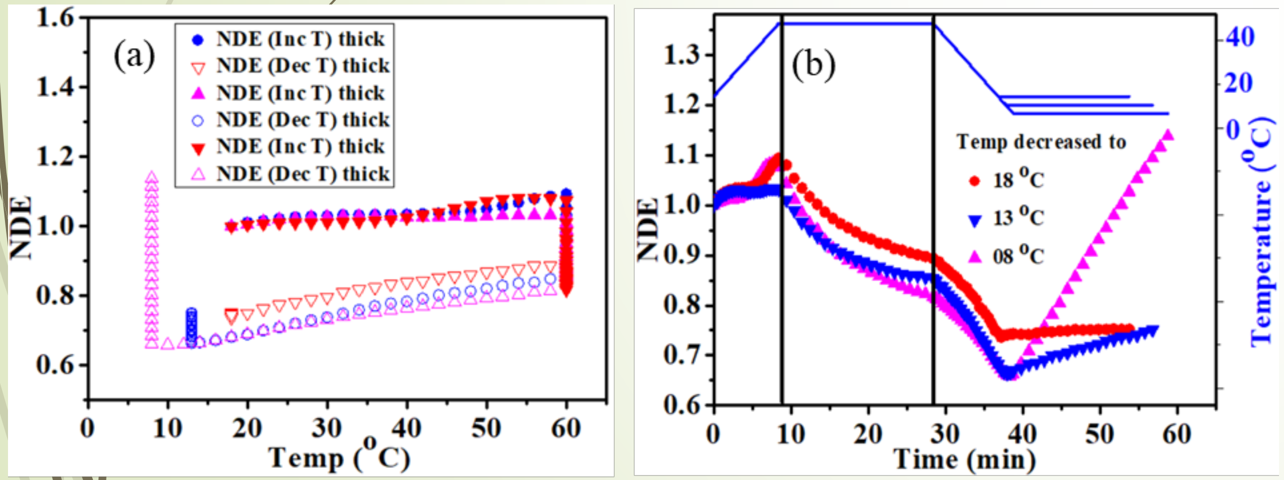


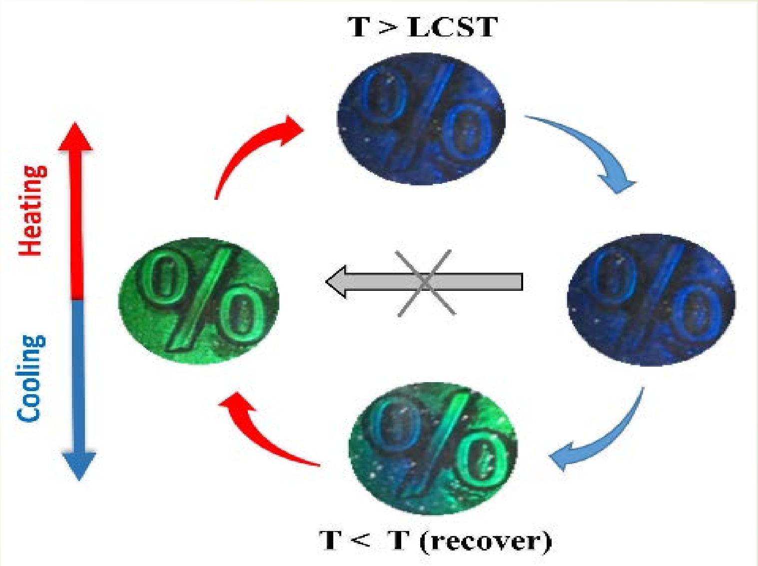
Poly(N-isopropylacrylamide) characteristics:

- *Lower Critical Solution Temperature (32 °C) : a sharp coil-globule transition.*
- *LCST: hydrophilic state hydrophobic state.*
- *Low toxicity.*

Electronic read-out

Visual read-out





Indicator of goods being exposed to above room temperature

Irfan et al, Adv. Photonics Res. 2021, 2, 2100062, DOI: 10.1002/adpr.202100062

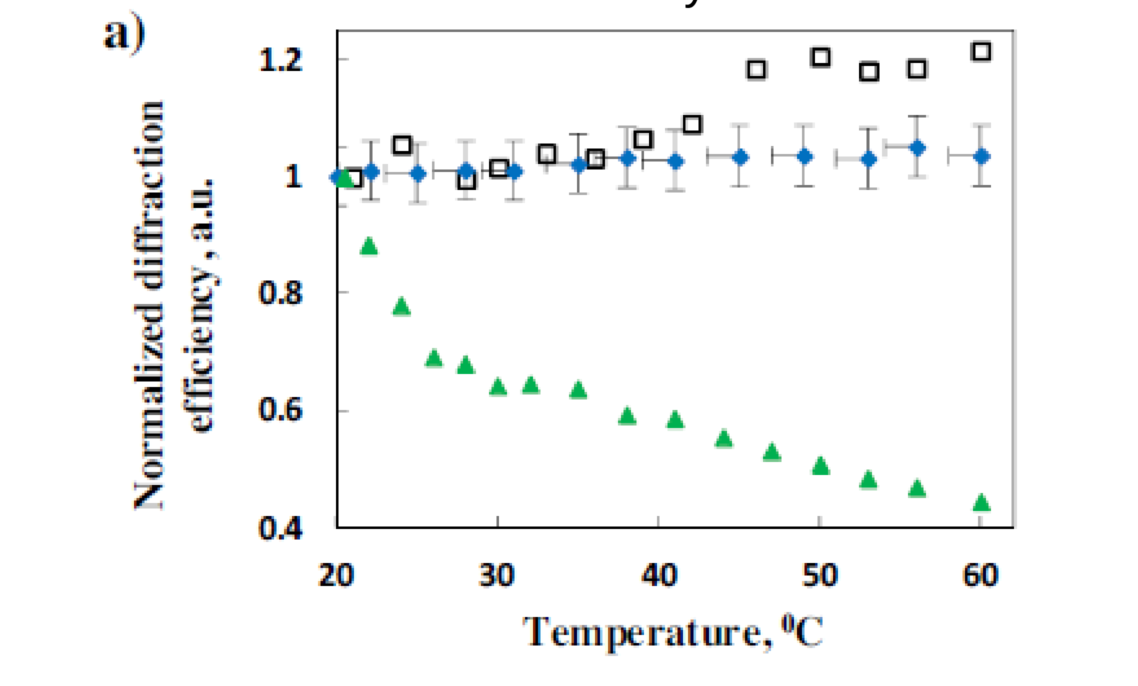
Holographic temperature sensor

Target application : **wound healing monitoring, mapping skin temperature: ranging from 31 to 38◦C**

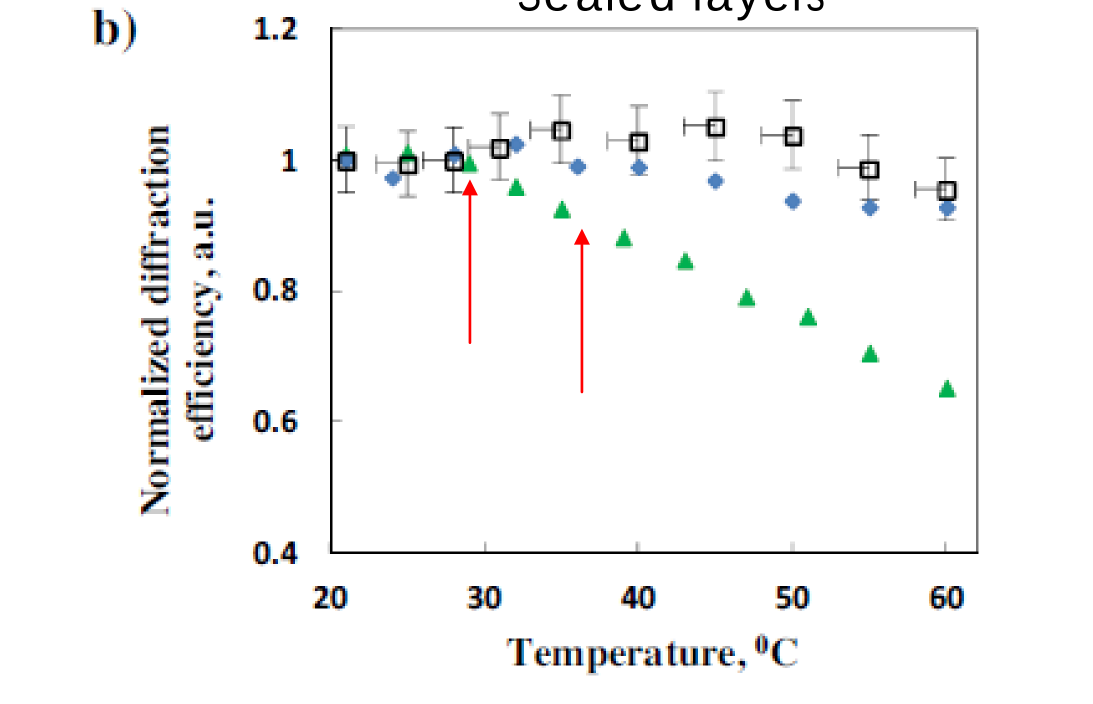
Transmission gratings recorded in three different hydrogel materials

Transmission gratings

Unsealed layers



Sealed layers



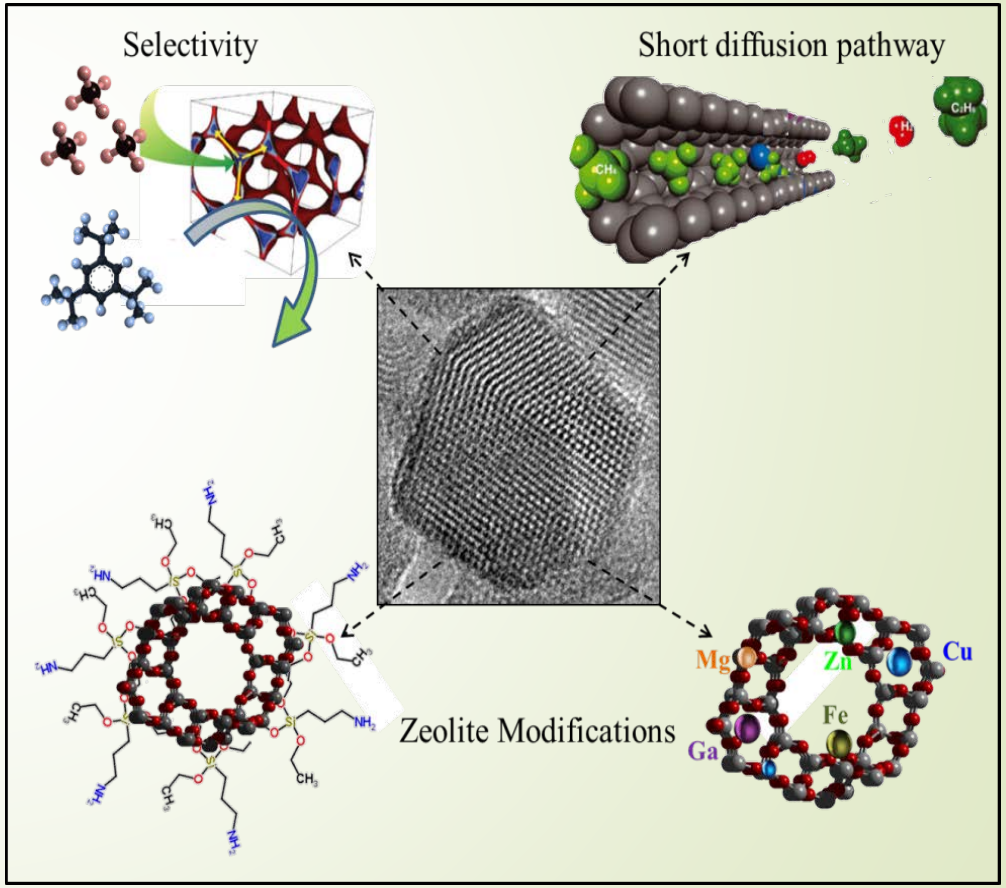
T. Mikulchyk et al. / Sensors and Actuators B 239 (2017) 776–785; http://dx.doi.org/10.1016/j.snb.2016.08.052

Functionalisation by incorporation of nanosize zeolites

- Versatility - pore structure, surface area, particle size and morphology, hydrophobicity / hydrophilicity

- Low scatter –good optical quality nanocomposite films

- Stable suspensions, suitable pH, large variety of refractive indices

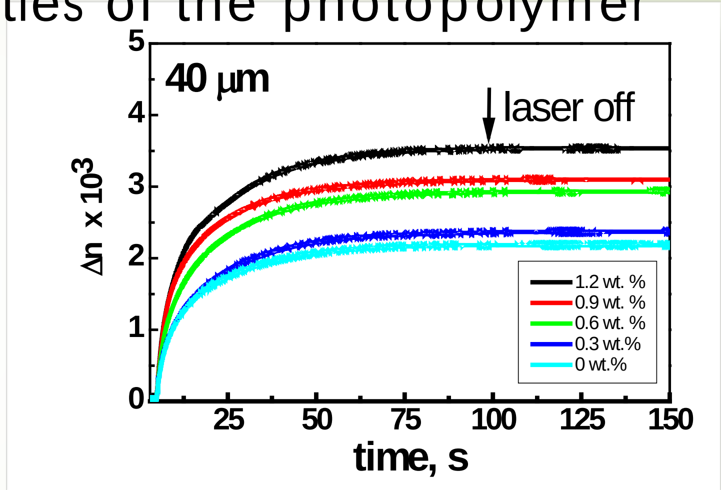


Functions of zeolite nanoparticles in photopolymers

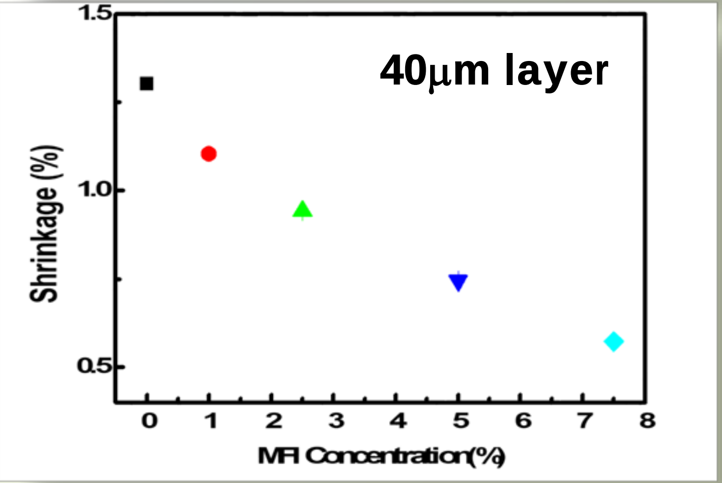
- Alteration of the effective refractive index/refractive index modulation
- Modification of the mechanical properties of the photopolymer and its ability to shrink /swell
- Sensing properties

Photopolymer layer

Improved dynamic range



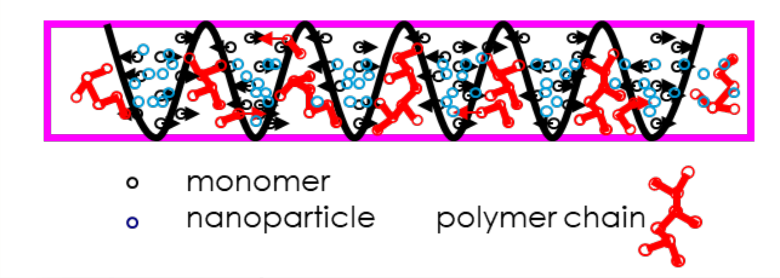
Decreased shrinkage



Methods for incorporation of the zeolite nanoparticles to photopolymer layers

Mixed in photopolymer

Typical resolution ~300 nm

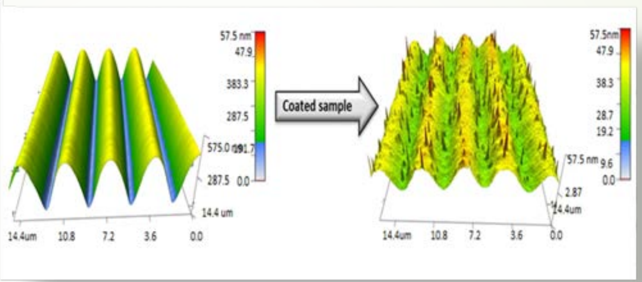


Before recording - homogeneously distributed throughout the layer

Patterning by holographic recording and polymerisation driven diffusion of photopolymer components

Spin-coating

Typical resolution ~1-5 μm

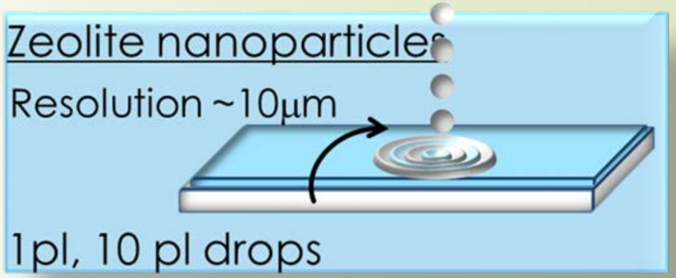


Thin layer ~ 200 nm, lower sensitivity

Faster response time

Flexible functionalisation

Ink-jet printing



Controlled amounts of zeolites

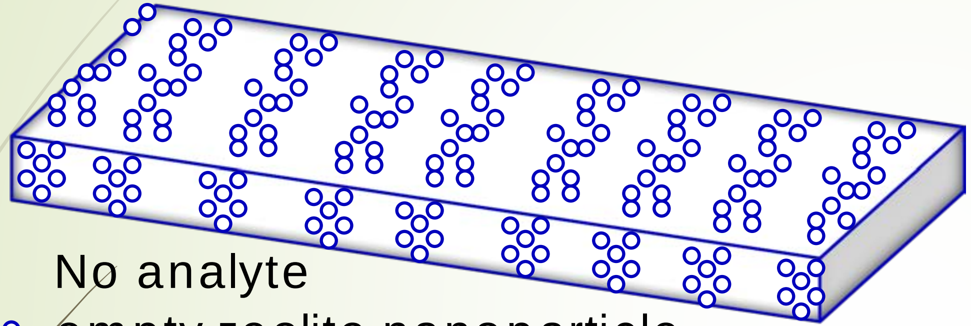
Patterning by localised deposition of the nanoparticles

More than one zeolite on one sensor

Zeolite doped transmission holograms

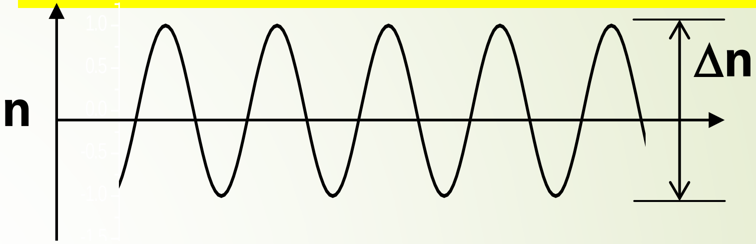
Spatial redistribution of zeolite nanoparticles during holographic recording

Spatial variation of the refractive index of the layer



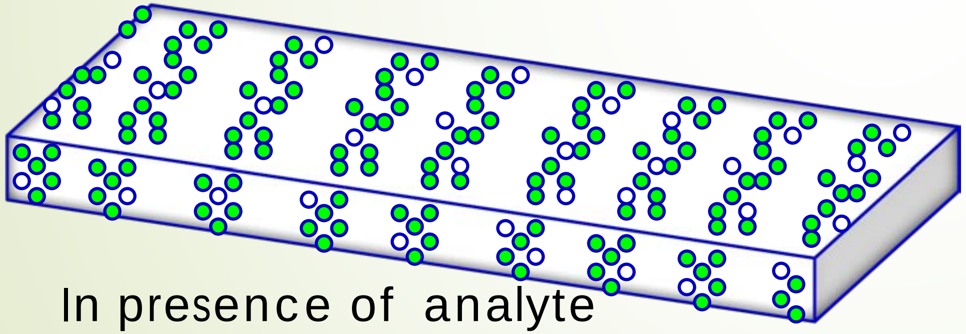
No analyte

∘ empty zeolite nanoparticle



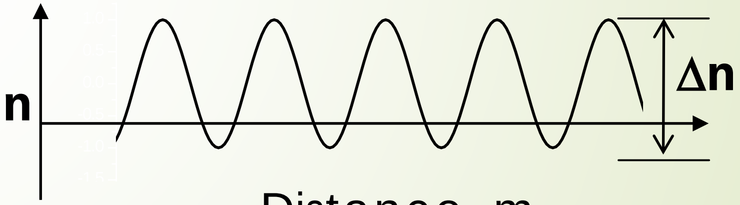
Distance, m

High diffraction efficiency



In presence of analyte

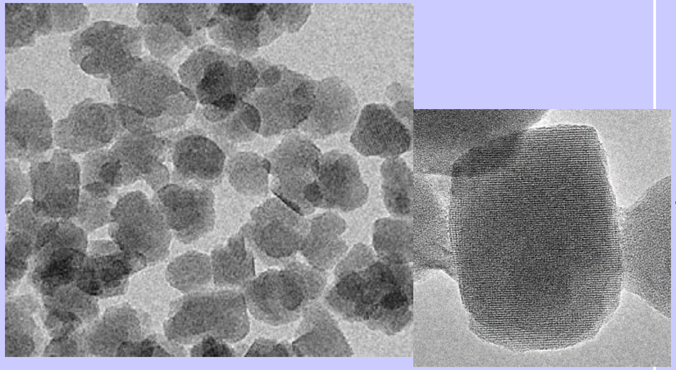
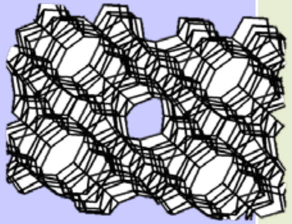
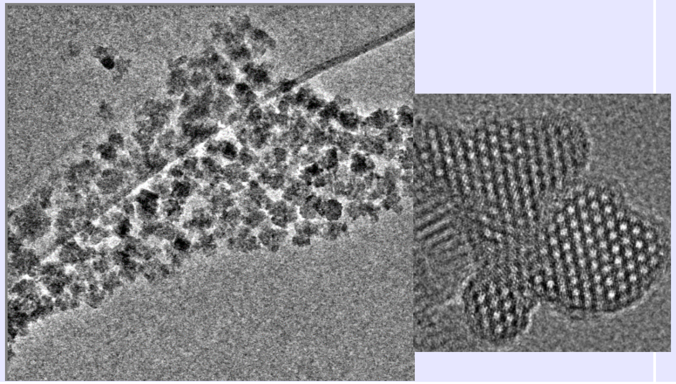
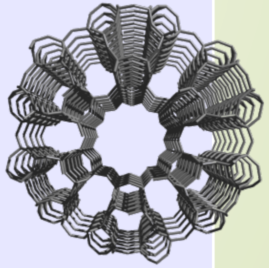
• zeolite nanoparticle with adsorbed analyte



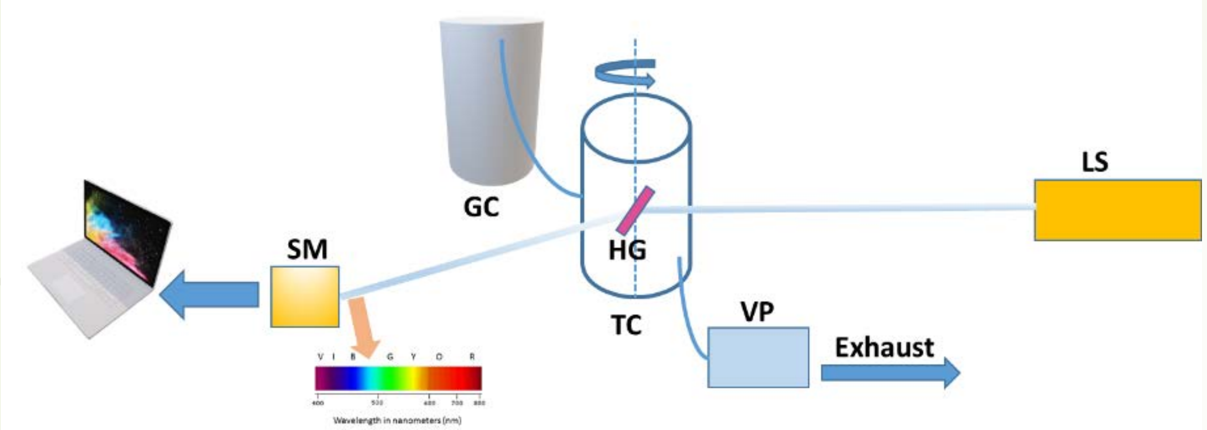
Distance, m

Low diffraction efficiency

$$\Delta n_{nano} = \frac{2 f_{nanodopants}}{\pi} (n_{nanodopant} - n_{host}) \sin(\alpha\pi)$$

Zeolite nanoparticles	Characteristics
MFI 	Size ~30 nm Pore openings 5.5 Å **3D structure** H_2O= 4 % 
LTL 	Size ~30 nm Pore opening 7.1 Å **1D structure** H_2O= 16 % 

Controlled gas environment



GC - Gas storing chamber
SM - Spectrometer
LS - Light Source
TC - Testing Chamber
VP - Vacuum pump
HG - Holographic grating.

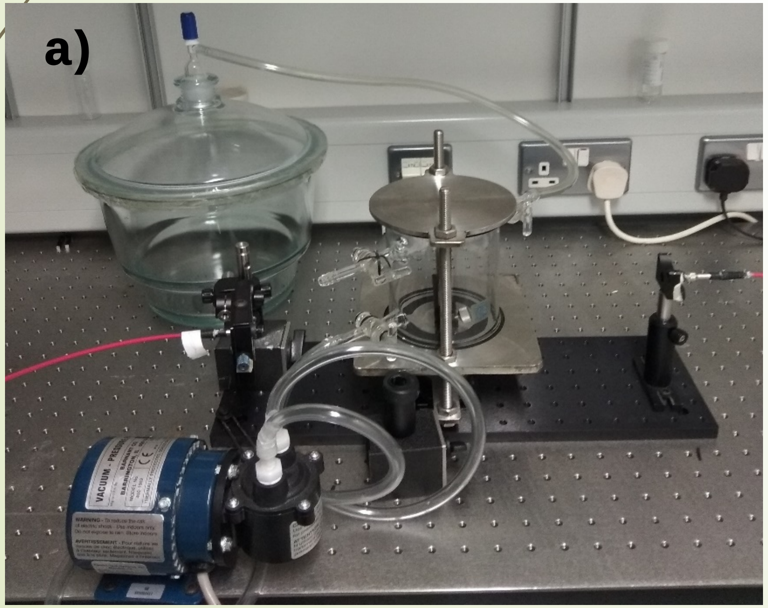


Figure : Photograph of gas exposure and characterization setup; **(a)**, and gas testing chamber **(b)**

Exposure to toluene of slanted holographic gratings (Graceson Anthony, PhD student)

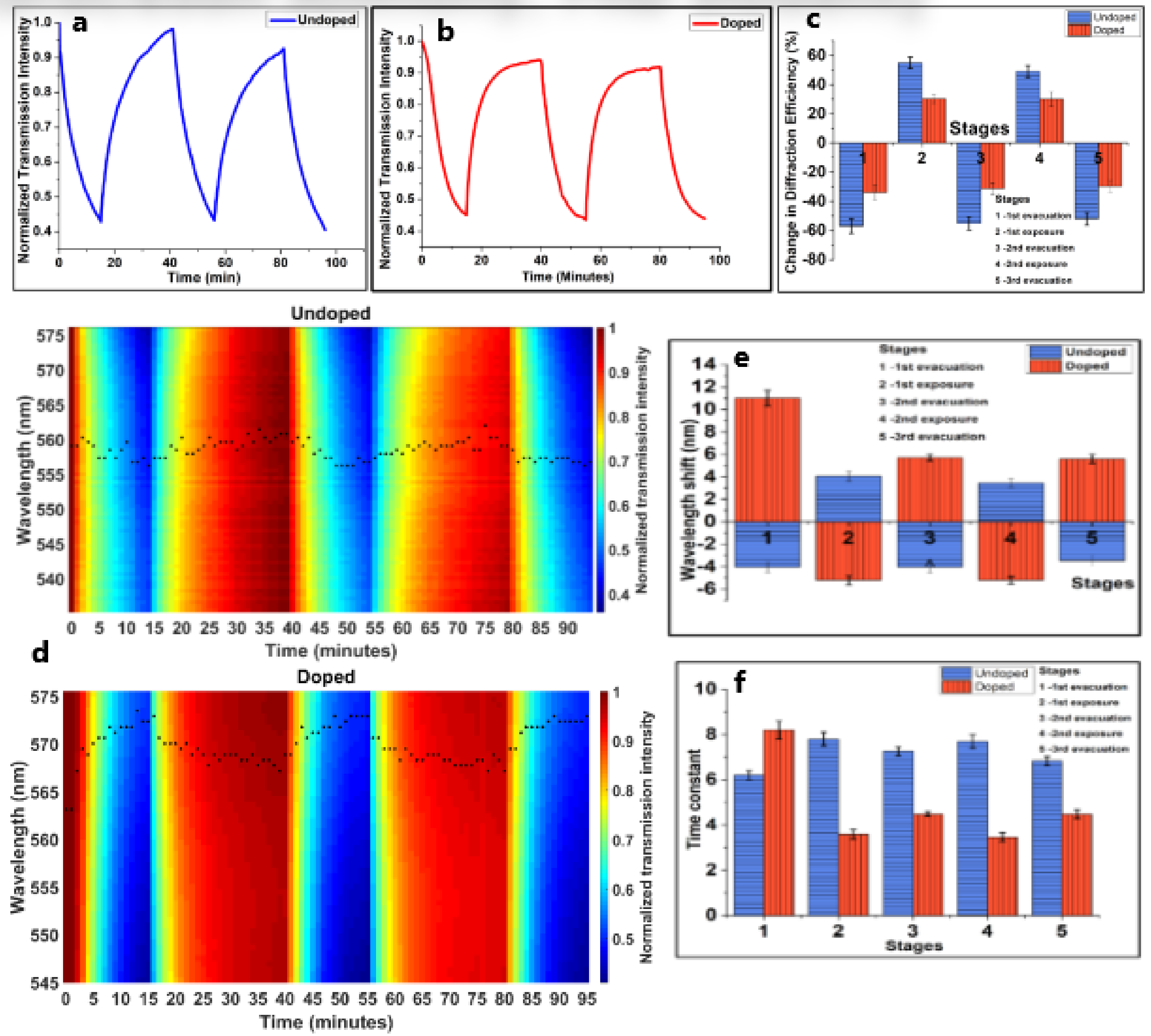


Figure: Sensor response of diffraction efficiency of undoped sample (a), and doped sample (b). Change in diffraction efficiency at each stage of evacuation and toluene exposure for undoped and doped samples (c). Peak wavelength shift and intensity variation in the diffracted beam (d), peak wavelength shift at each stage of evacuation and toluene exposure (e).Time constant at each stage of evacuation and exposure(f),

Theoretical analysis of sensor response

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\Lambda}{\Lambda} + \frac{\Delta n_{navg}}{n_{avg}} + \mathrm{Cot}(\theta - \Psi)(\Delta\theta - \Delta\Psi)$$

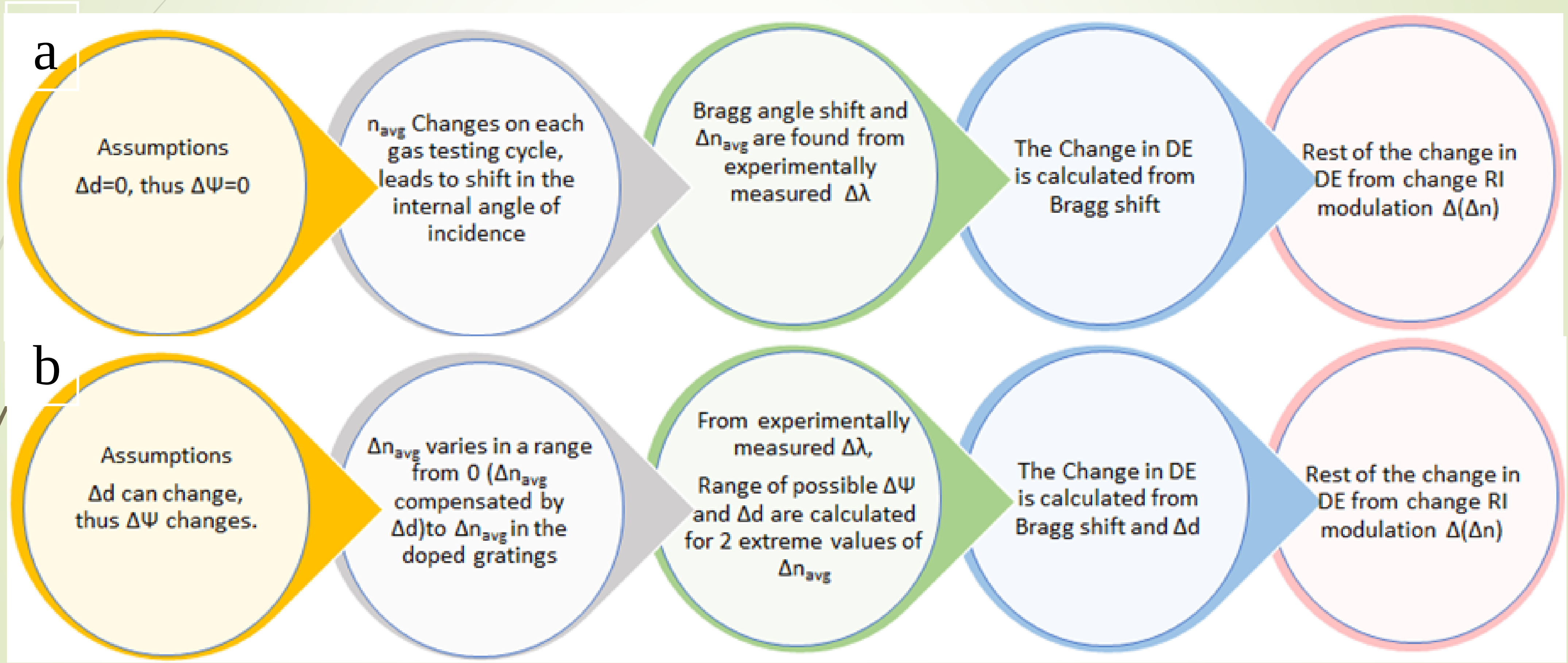


Figure: Assumptions and the steps utilised in analysing the response of sensors recorded in a) doped and b) undoped layers.

Results

The contribution of Δn_1, Δd, $\Delta\Psi$, $\Delta\theta_{probe}$ for the observed change in diffraction efficiency

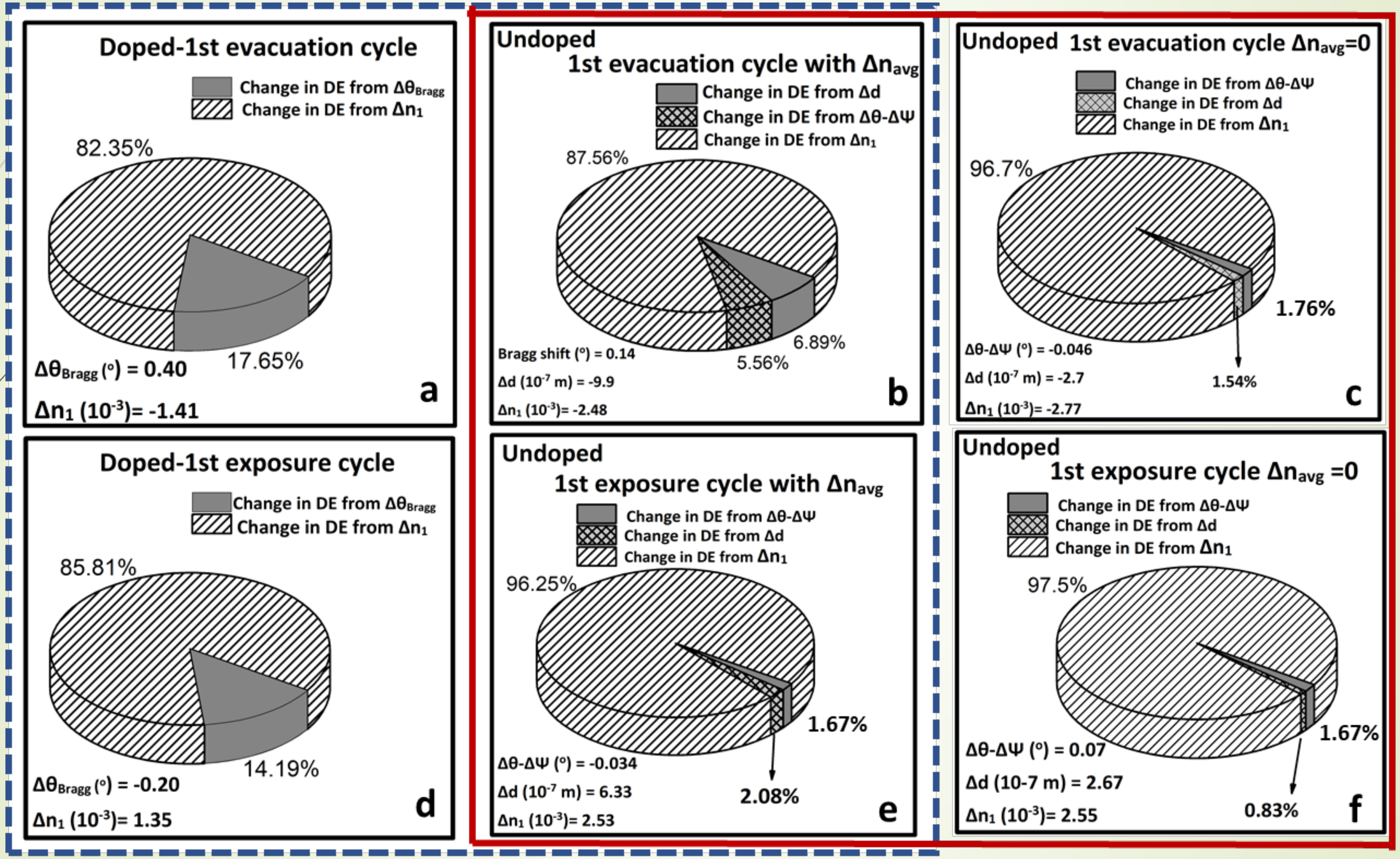


Figure: 1st evacuation and 1st exposure cycle of doped (a,d) and undoped (b,e) with Δnavg ≠ 0. 1st evacuation and 1st exposure cycle of undoped at $\Delta n_{avg} \neq 0$ (b, e), and at $\Delta n_{avg} = 0$ (c,f).

Zeolite doped layers

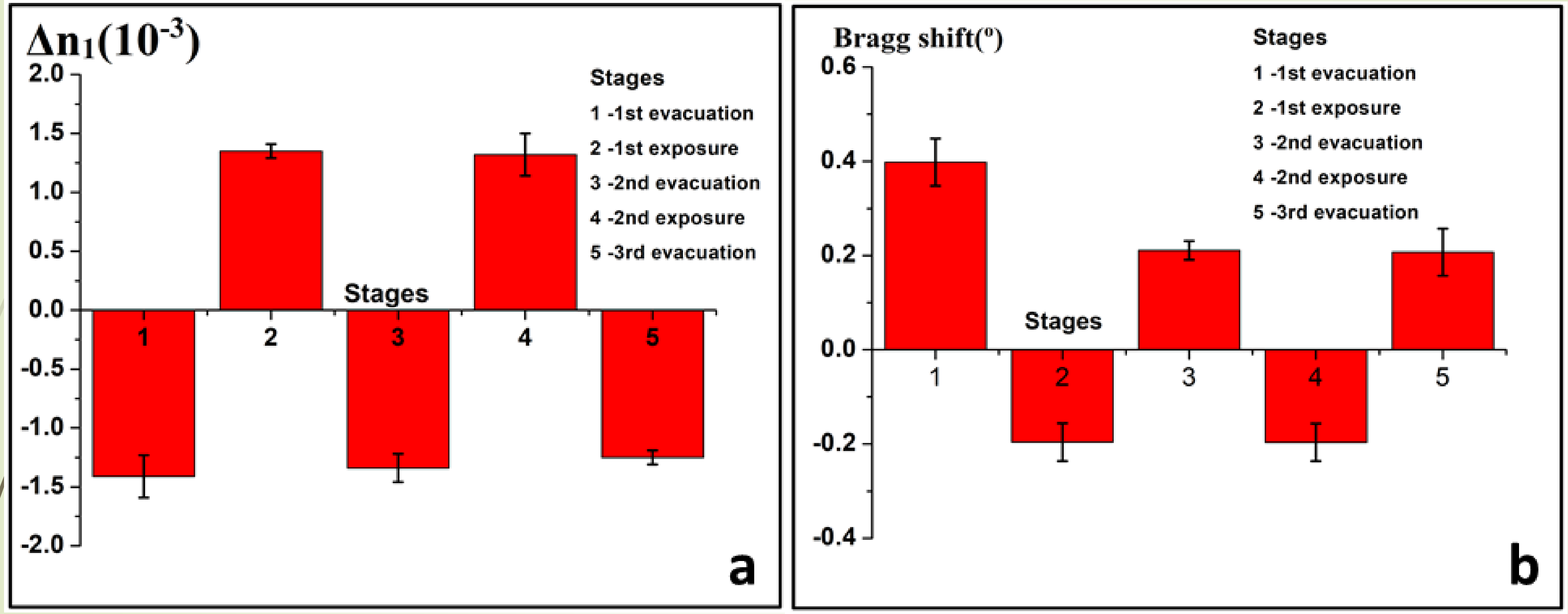


Figure: Estimated values of Δn_1 (a) and Bragg angle detuning (b) at different gas testing cycle of doped samples.

Undoped layers

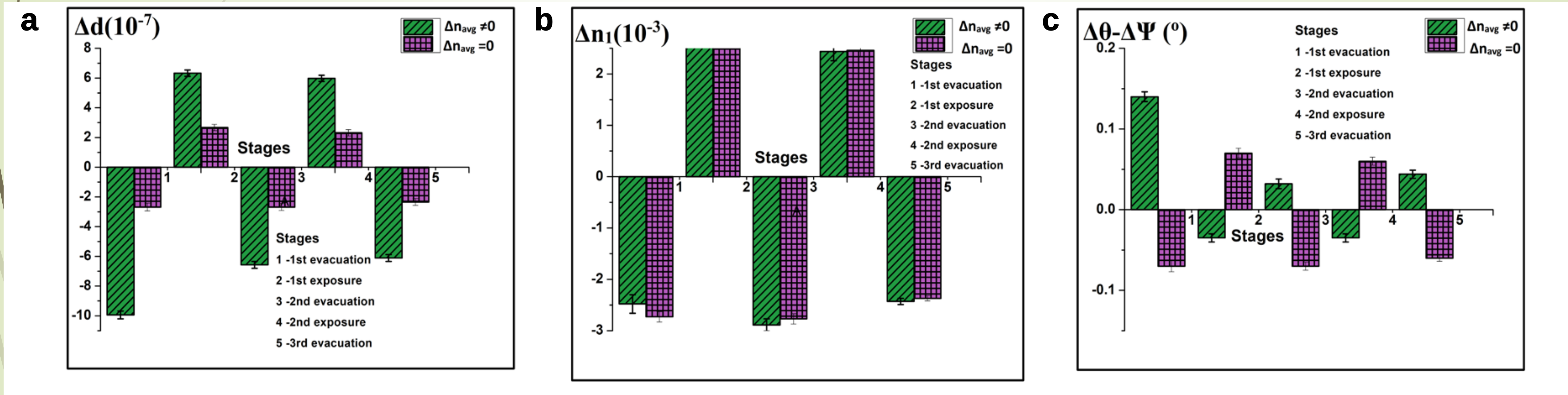
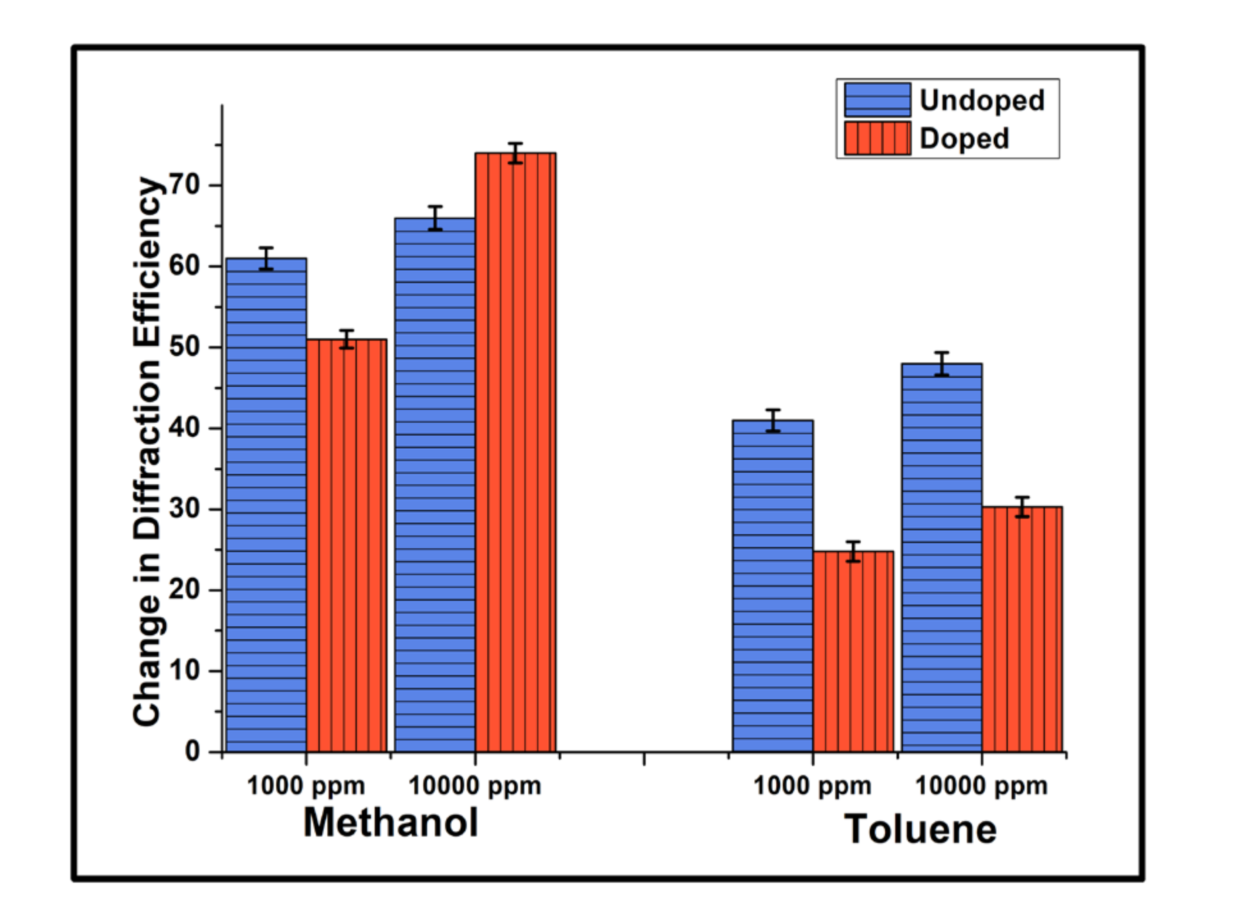


Figure: values of Δd (a), Δn_1 (b) and (Δθ- ΔΨ) (c) at different gas testing cycle of undoped samples at $\Delta n_{avg} \neq 0$ and $\Delta n_{avg}=0$

Response dependent on test molecule size



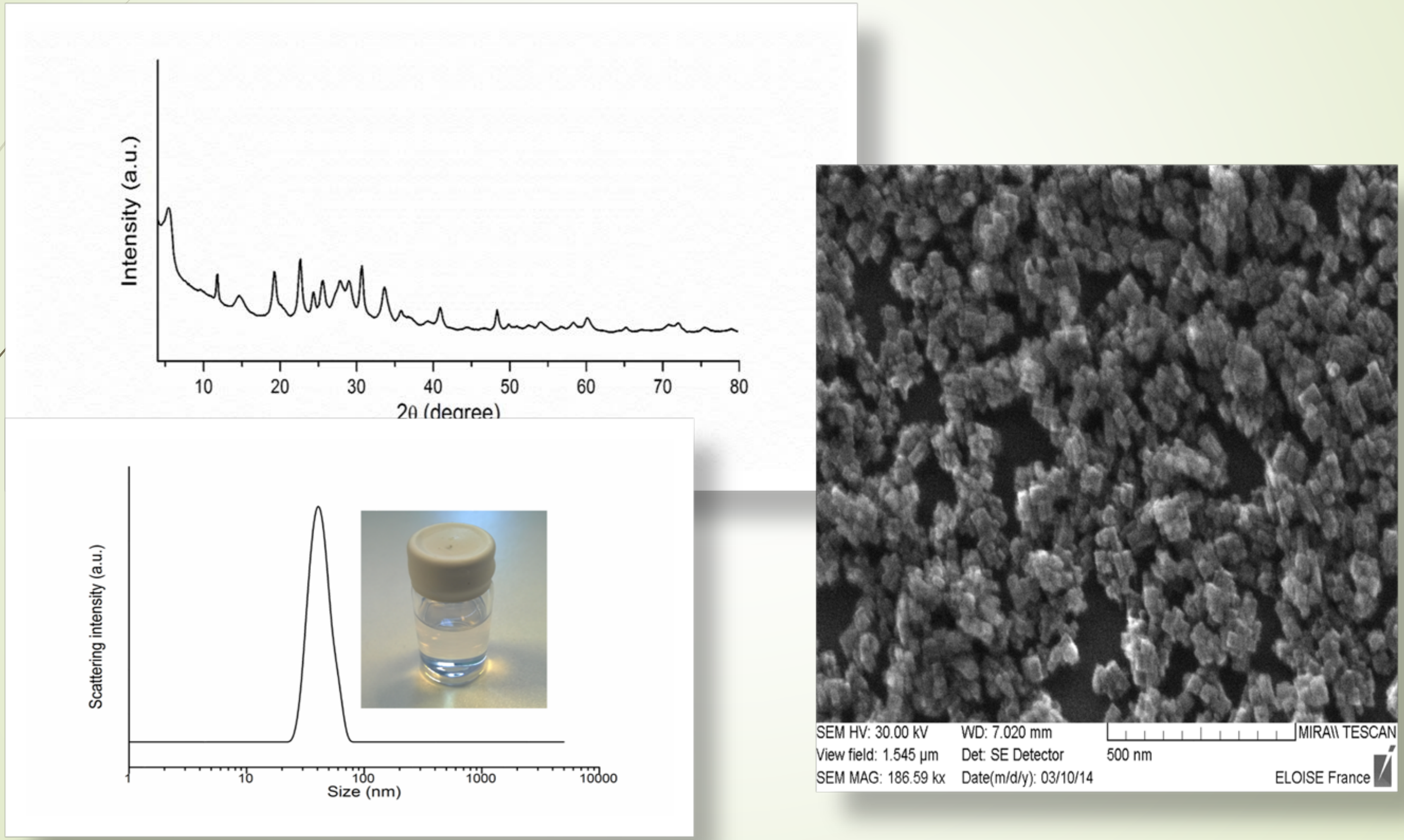
Exposure to methanol resulted in greater change in diffraction efficiency for both doped and undoped samples compared to toluene

Sensor based on SHG
(Dr Sabad e Gul)

Sabad-e-Gul, D.Cody, A.Kharchenko, S.Martin, S.Mintova, J.Cassidy, I.Naydenova, *Microporous and Mesoporous Materials*, 2018

Sabad-E Gul et al, Sensors 2019, 19 (5), 1026; doi:10.3390/s19051026.

Characterization of the LTL zeolites nanoparticles (Dr. Anastasia Kharchenko)

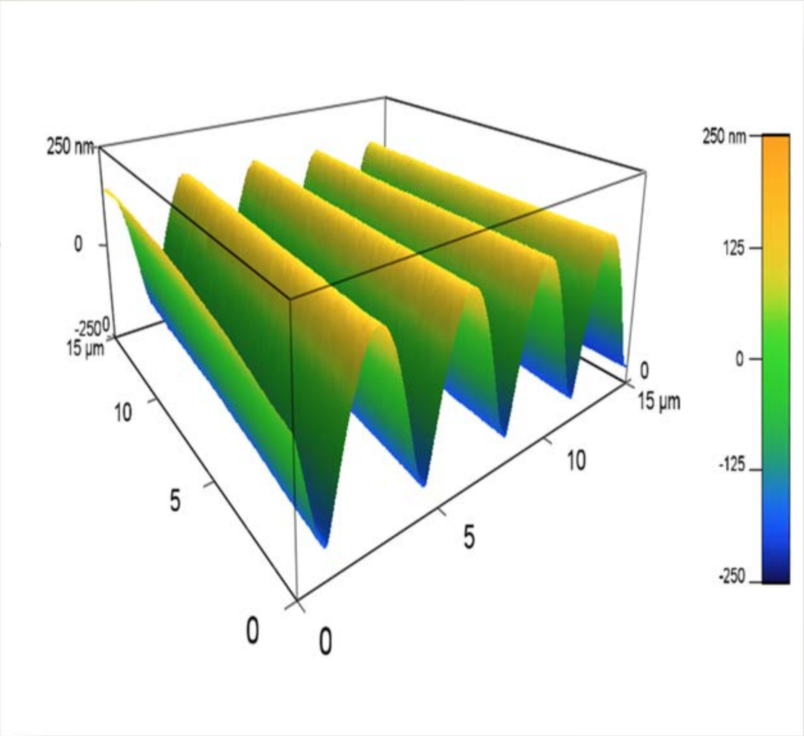


a) XRD patterns of LTL- powder (b) DLS studies (c) SEM studies

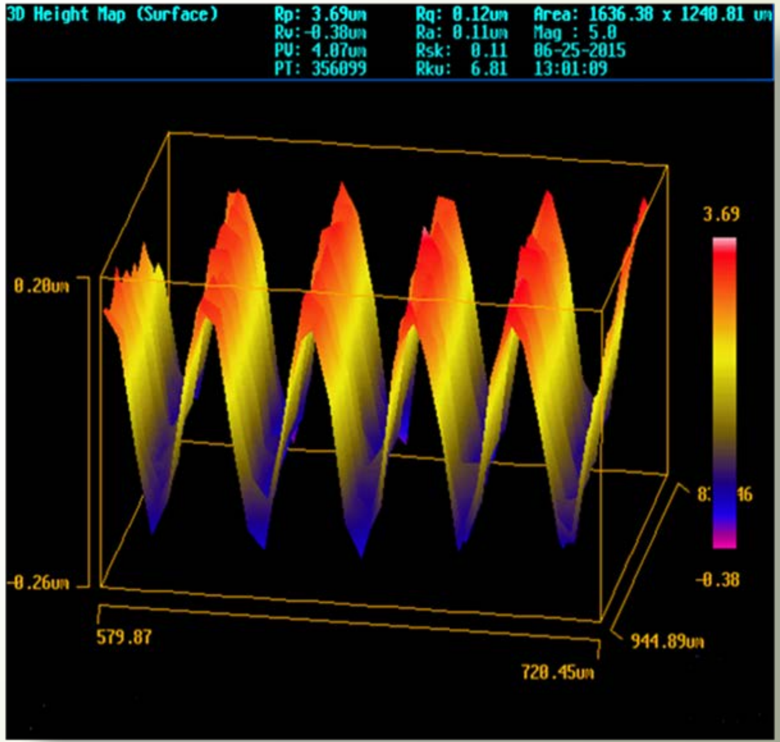
Surface structures (SRG)

- ❑ Surface profile characterization by AFM and WLI

- ❑ Surface modulation - 350nm- 400nm
- ❑ Period of the structures – 3μm

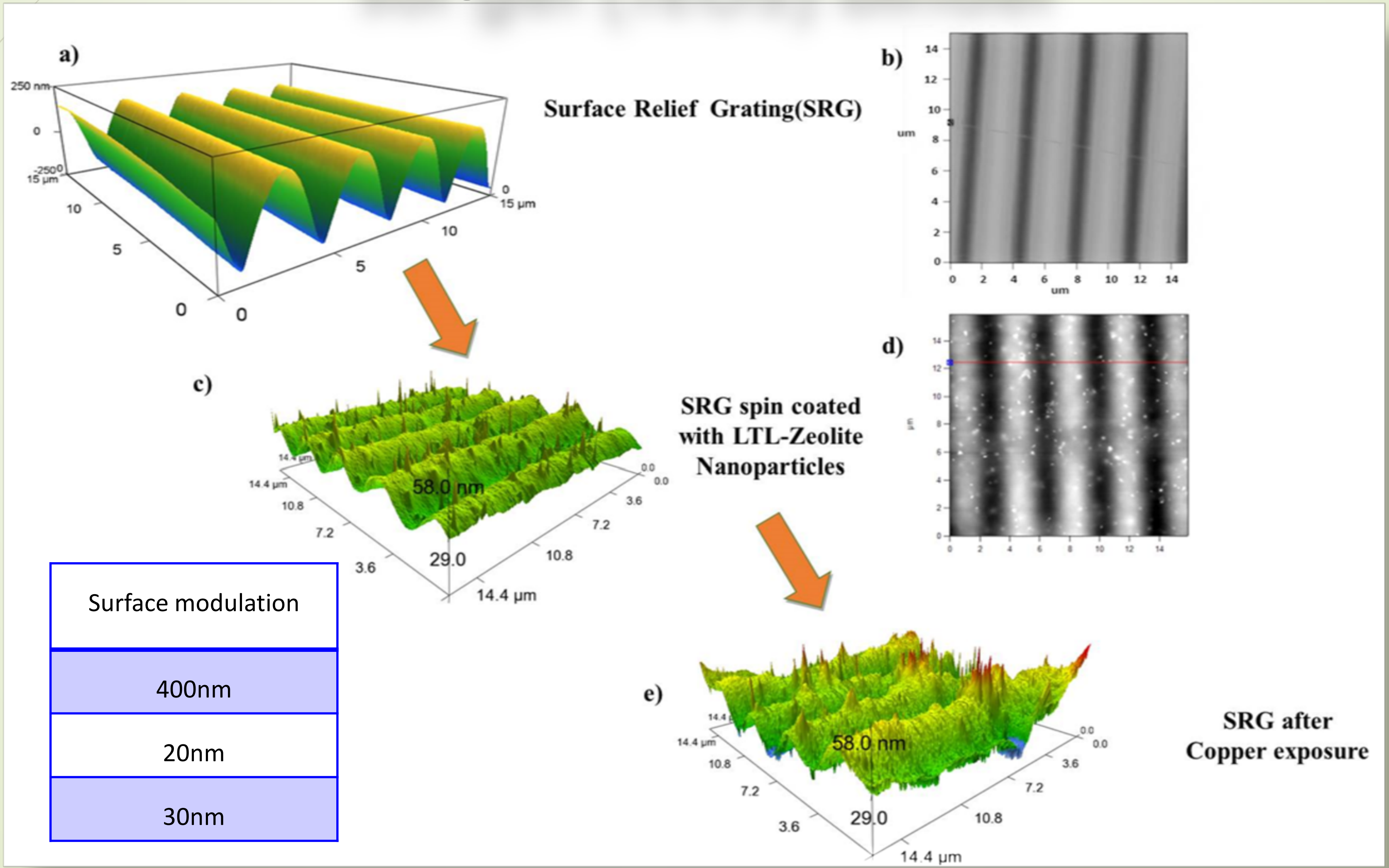


AFM study



WLI study

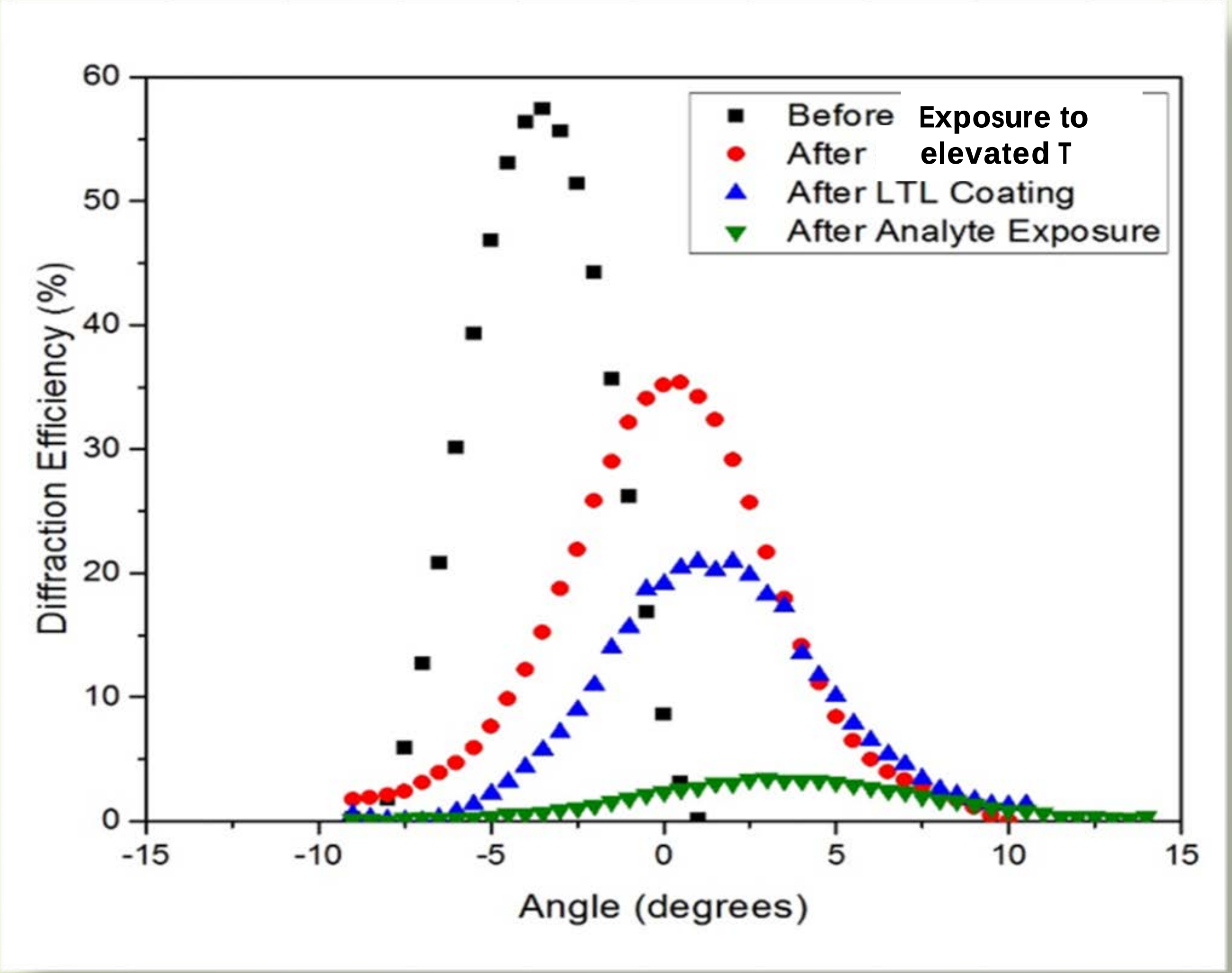
Surface photonic structures coated with LTL- zeolites nanoparticles dispersed in a sol gel (TEOS) binder



Surface modulation
400nm
20nm
30nm

LTL
2.7 wt %

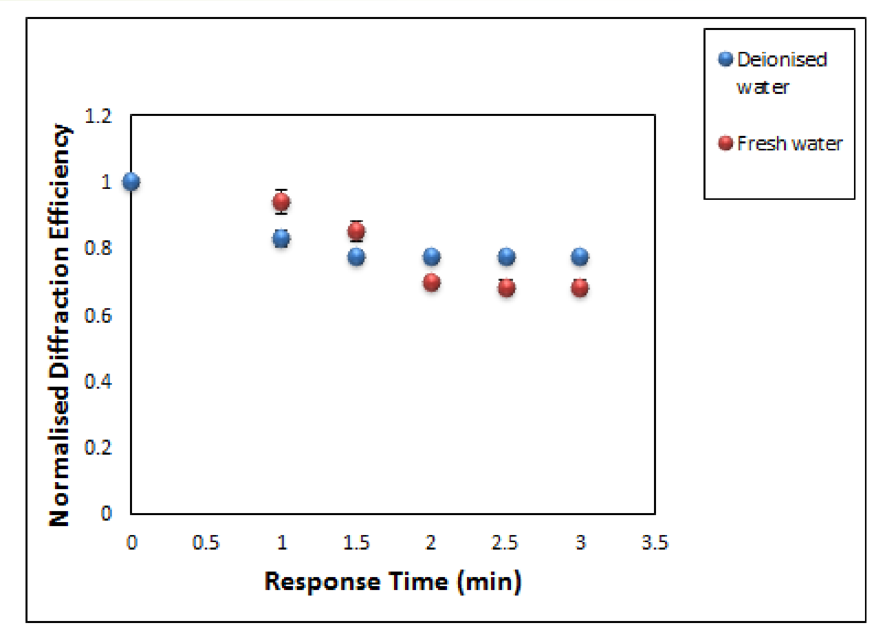
Bragg selectivity curves at different stages of the experiment

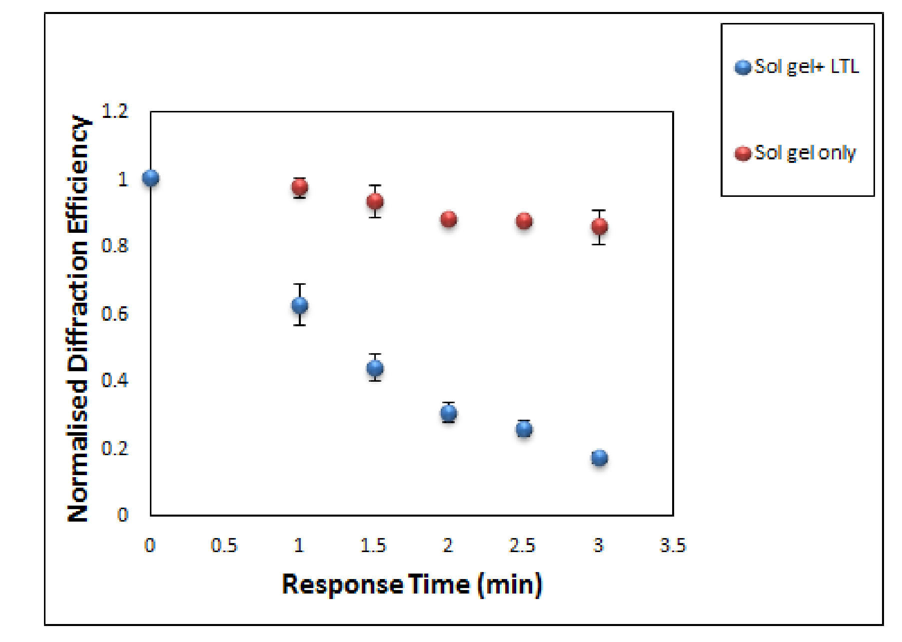


Experimental procedure
Reference tests

Following the 20% DE → Gratings were exposed to Cu solution for 1 min → Gratings were dried and measured DE → Gratings were again exposed to Cu solution for another 30 seconds and follow the same procedure until 3mins

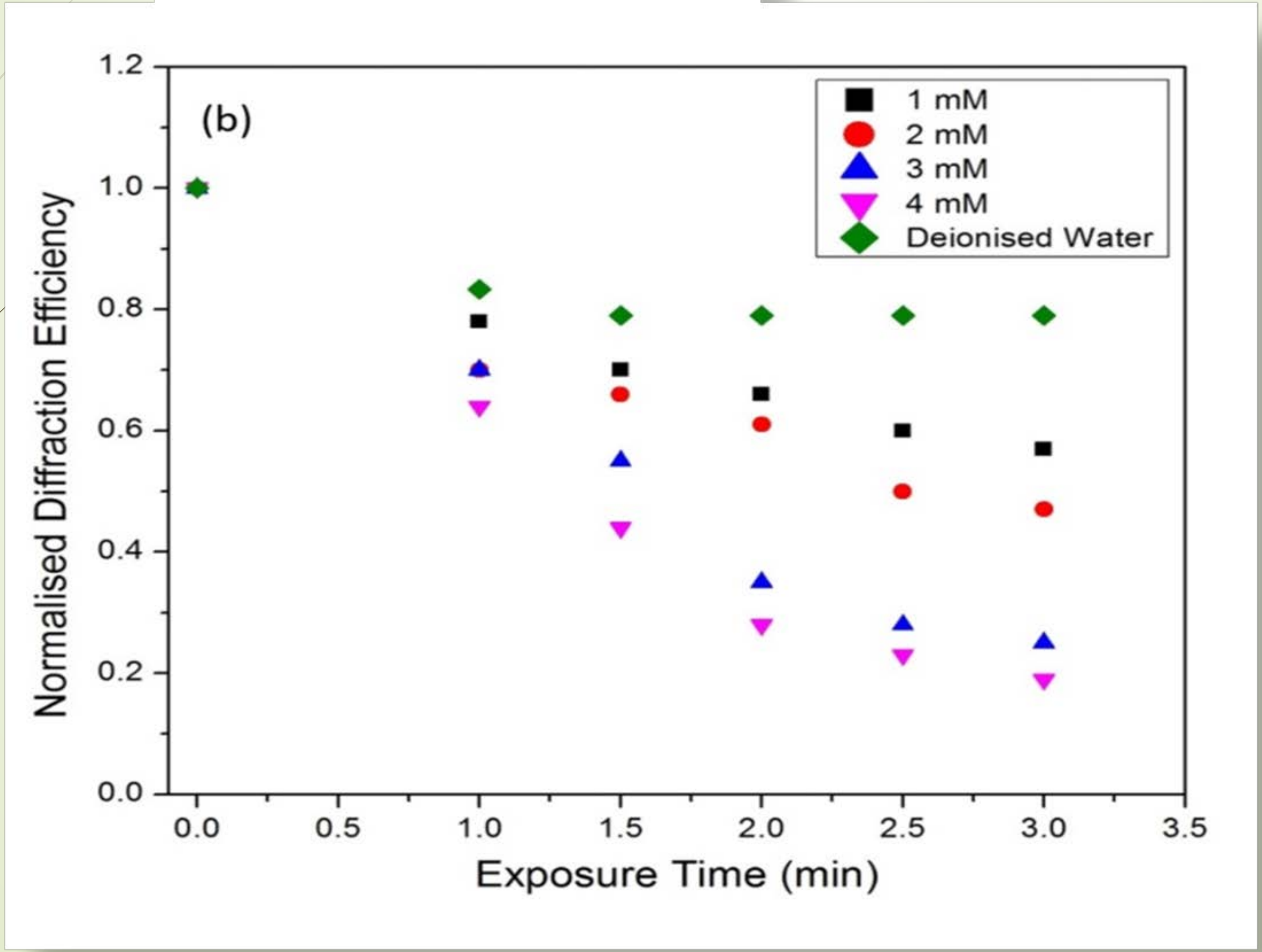
$Cu^{2+}SO_4.5H_2O$, 4 mM



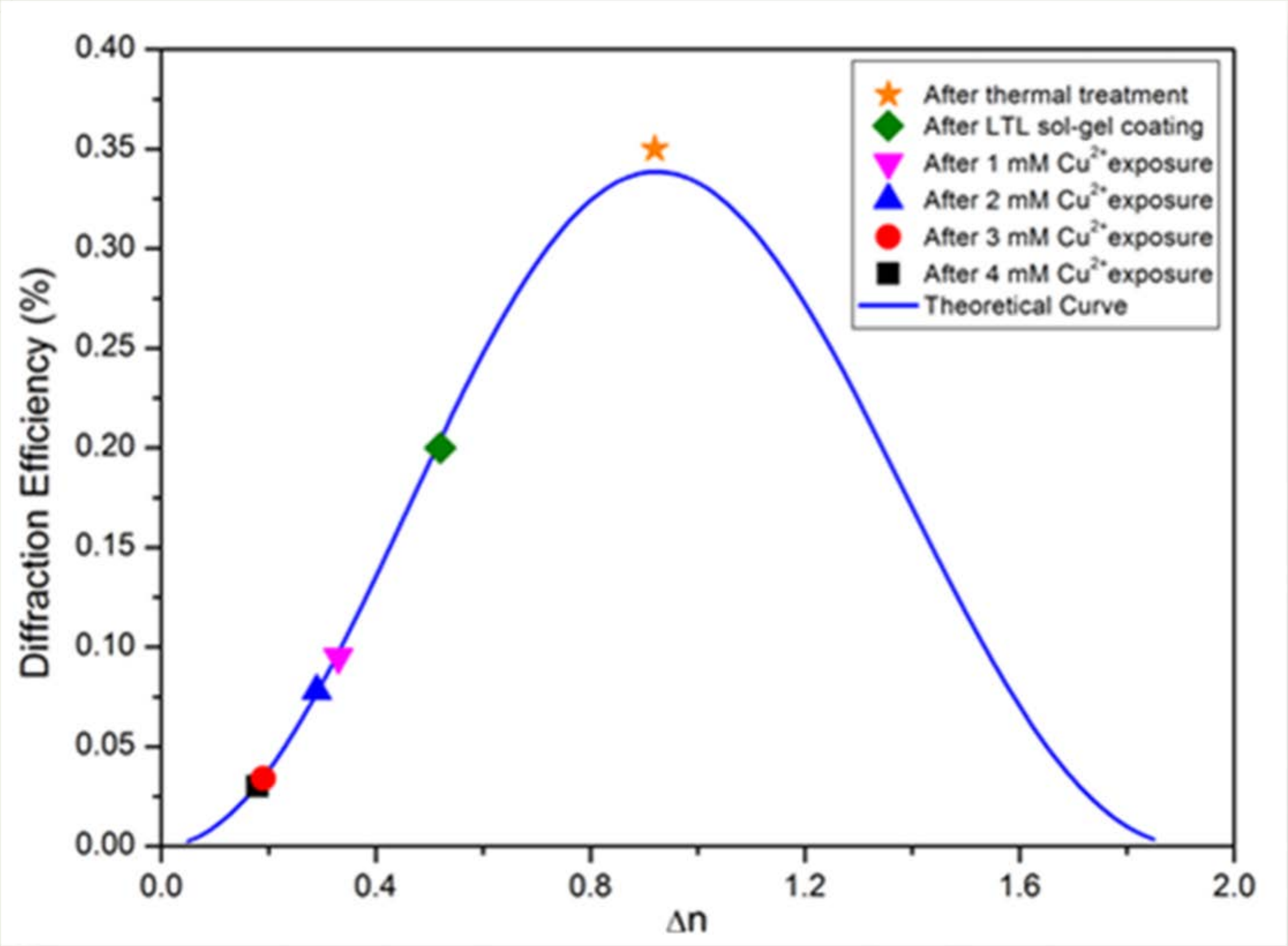


Experimental Results: Exposure to Cu^{2+} ions

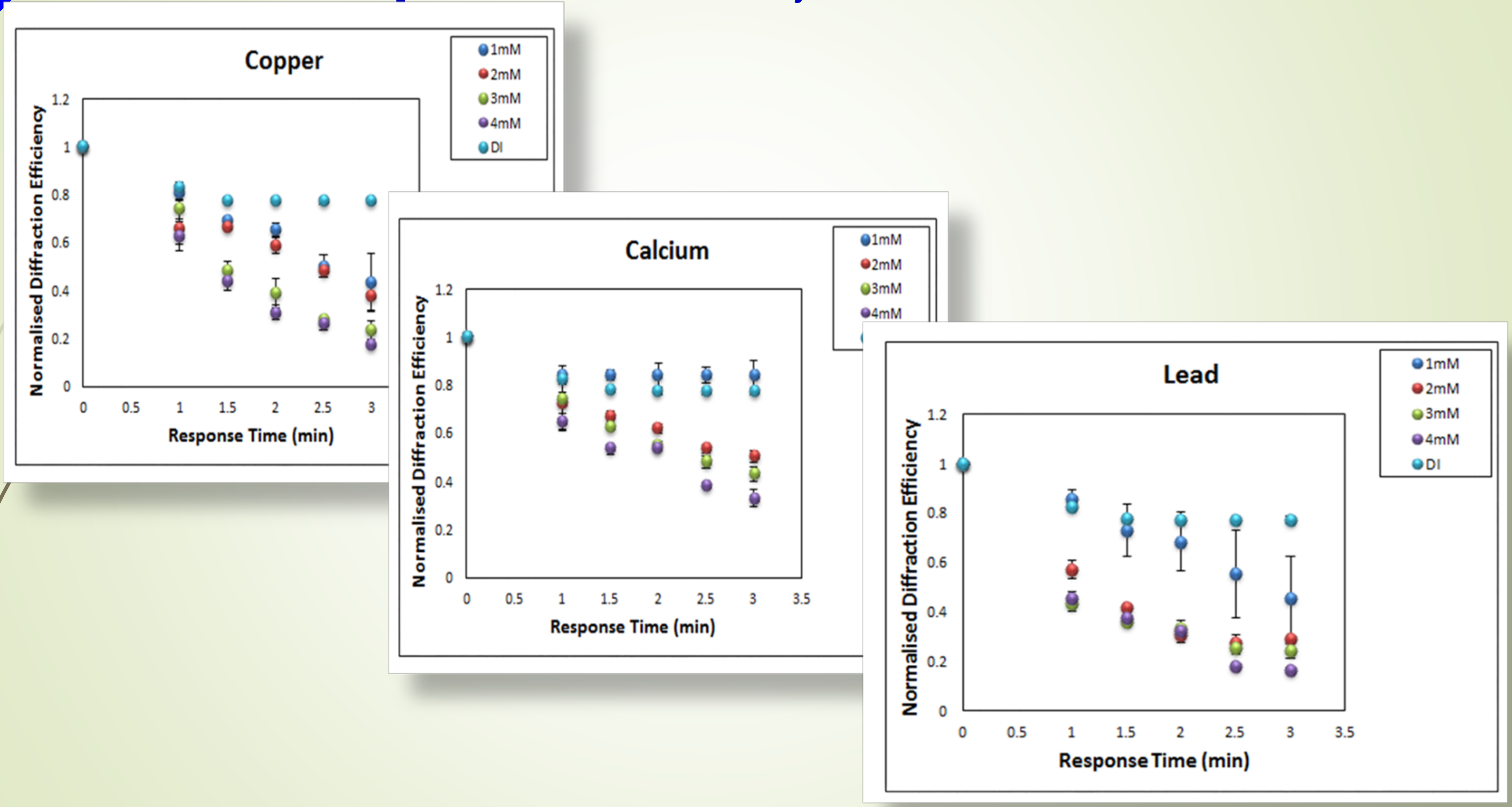
Cu^{2+}



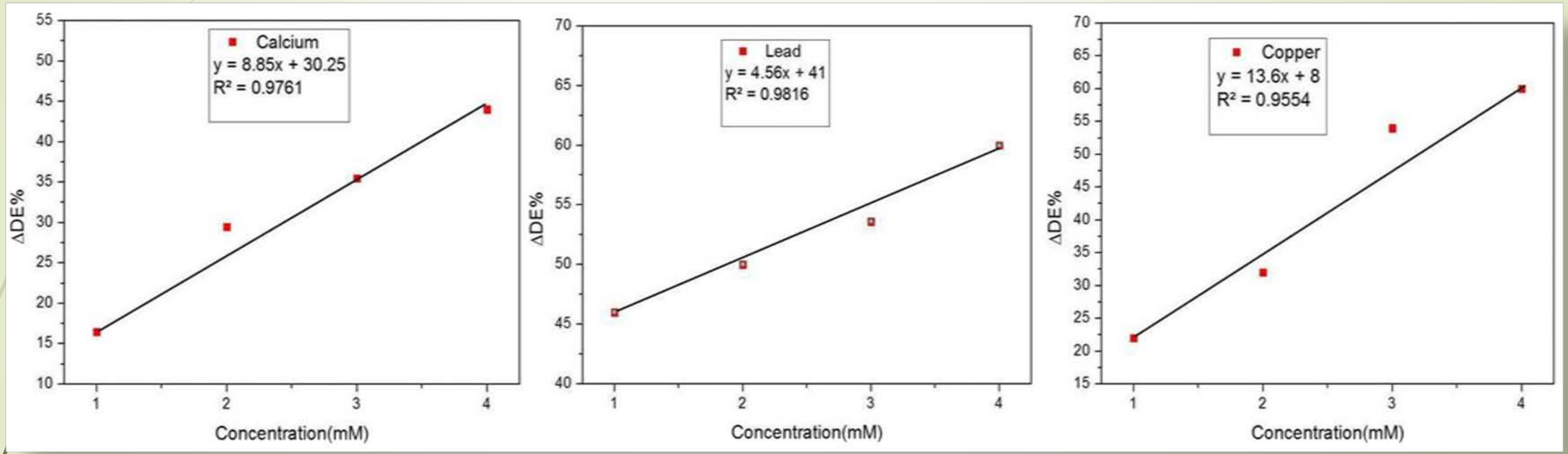
Experimental data/Theoretical model



Results: Exposure to Cu^{2+}, Ca^{2+} and Pb^{2+} ions

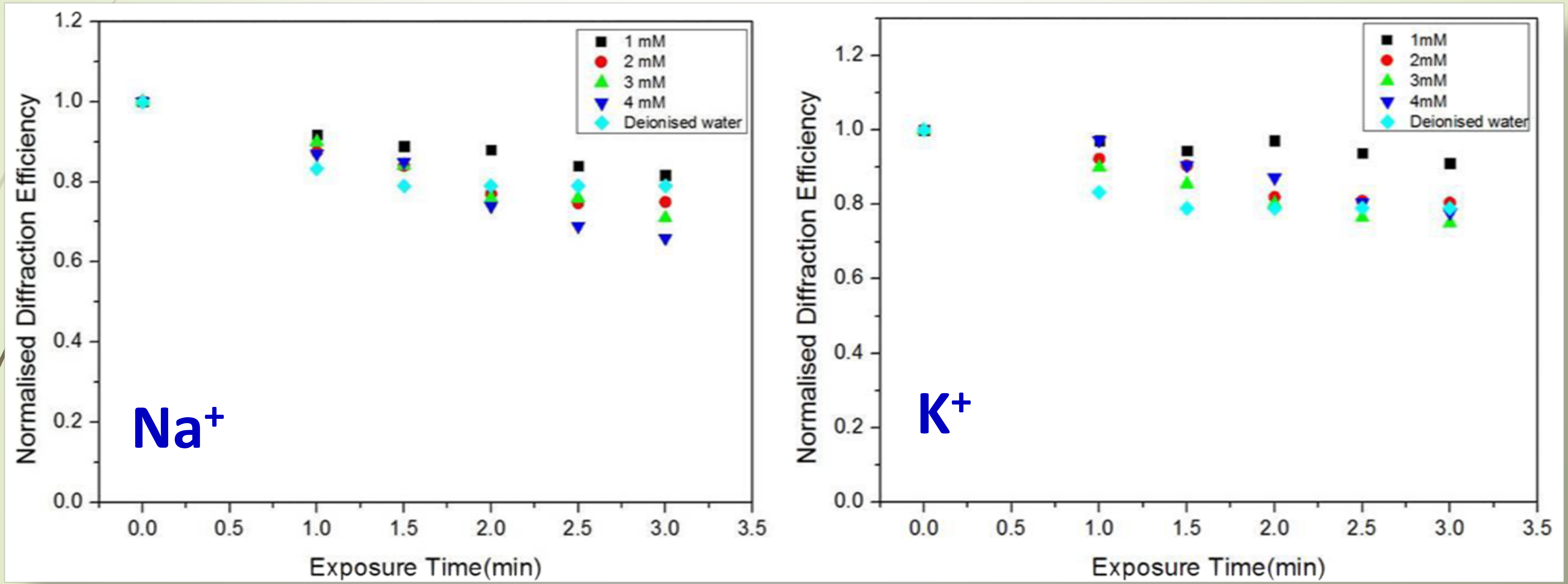


Sensitivity studies Cu^{2+}, Ca^{2+}, Pb^{2+}

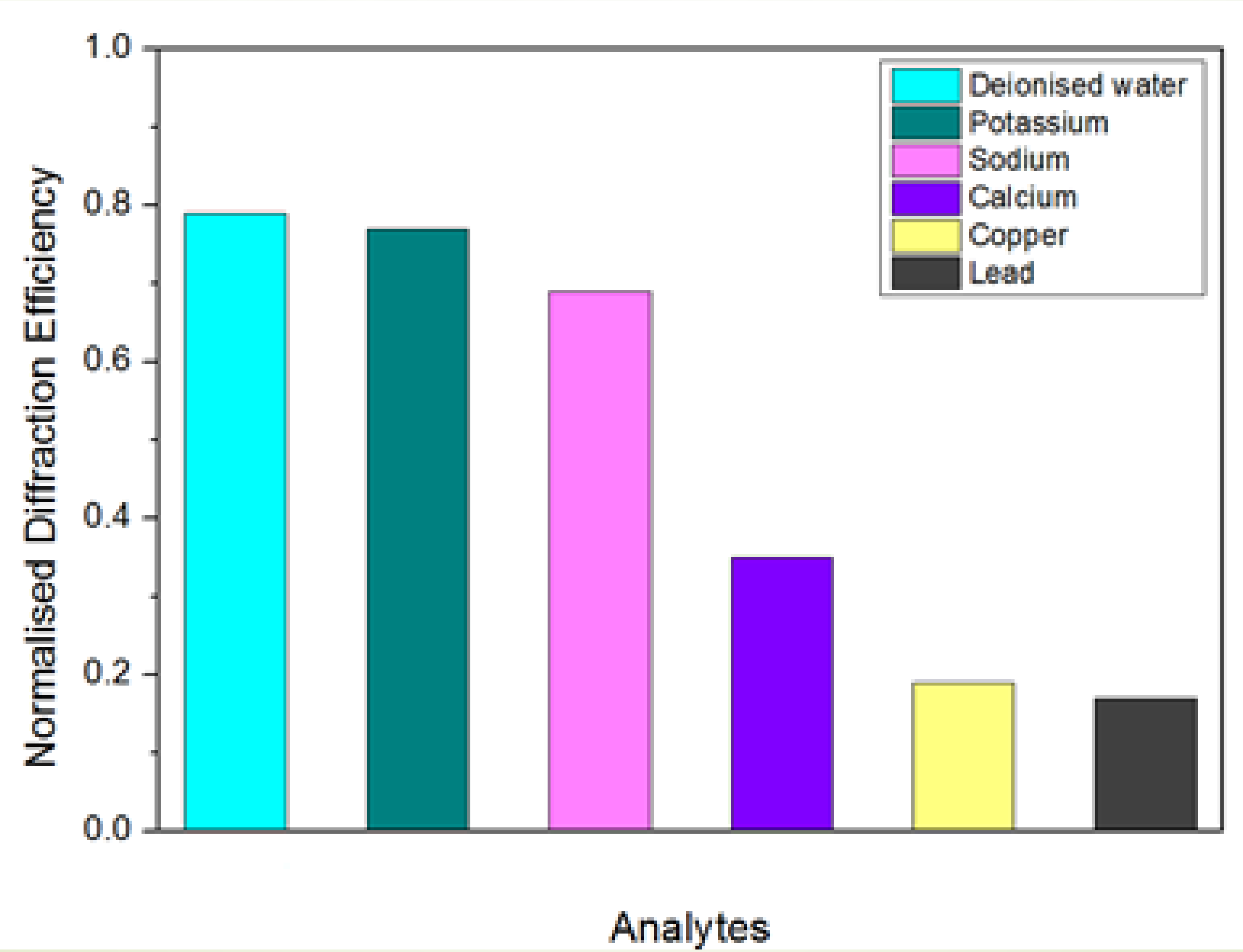


LOD Cu^{2+} **1.15 mM**
Ca^{2+} **0.82 mM**
Pb^{2+} **0.73 mM**

Results: Exposure to Na^+, K^+ ions

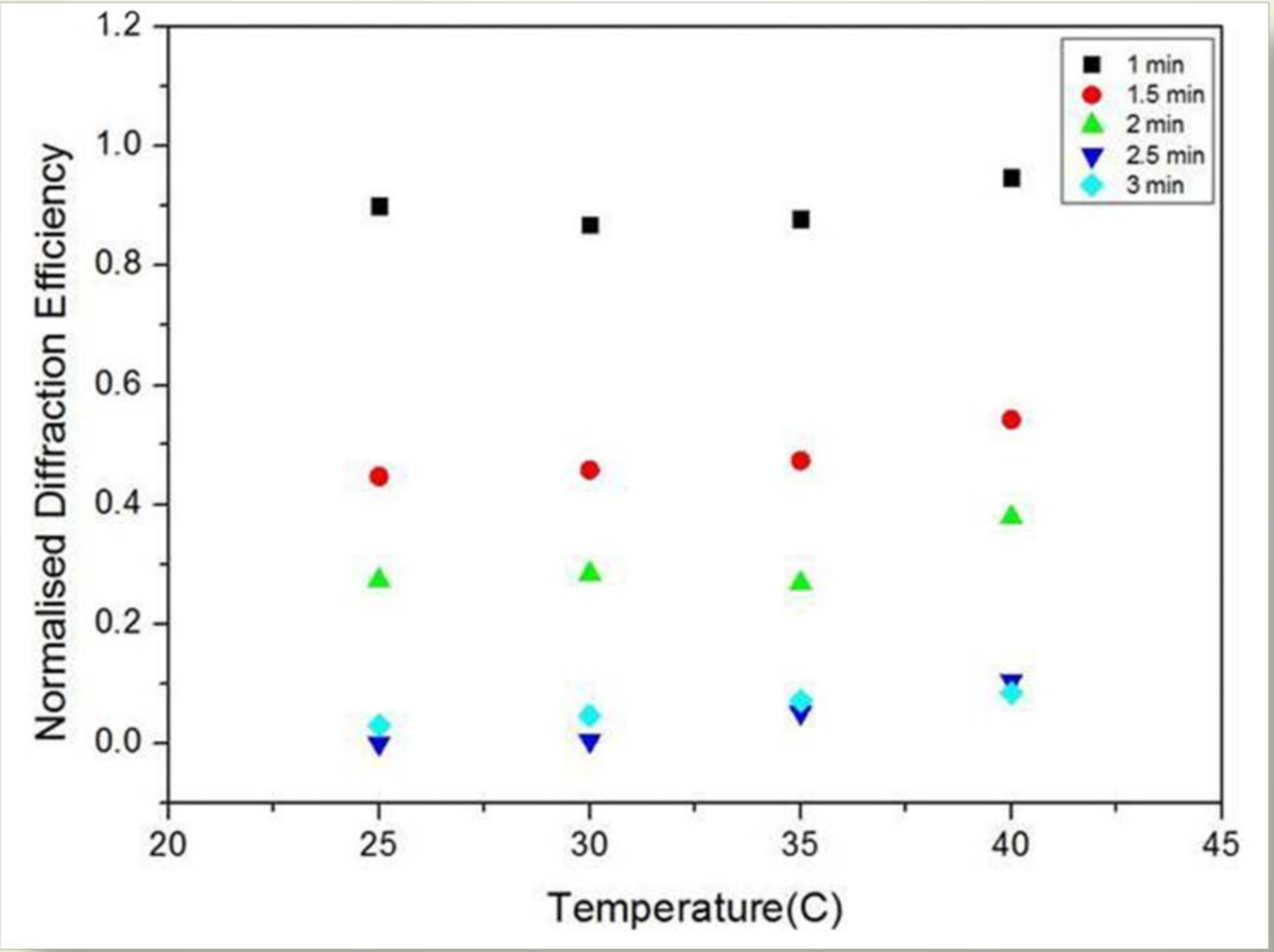


Metal ion detection: selectivity study



D.Cody et al. *Applied Optics, 2018, https://doi.org/10.1364/AO.57.00E173*

Temperature studies (Exposure to Cu^{2+})



Sensor based on Aztec gratings

Humidity sensor
(Collaboration with Dr Ali K. Yetisen)

Sensors based on Aztec grating

United States Patent [19] — **Cowan**

[11] **Patent Number:** 4,874,213

[45] **Date of Patent:** Oct. 17, 1989

[54] **METHOD OF FORMING VOLUME PHASE REFLECTION HOLOGRAMS**

[75] Inventor: **James J. Cowan**, Lexington, Mass.

[73] Assignee: **Polaroid Corporation**, Cambridge, Mass.

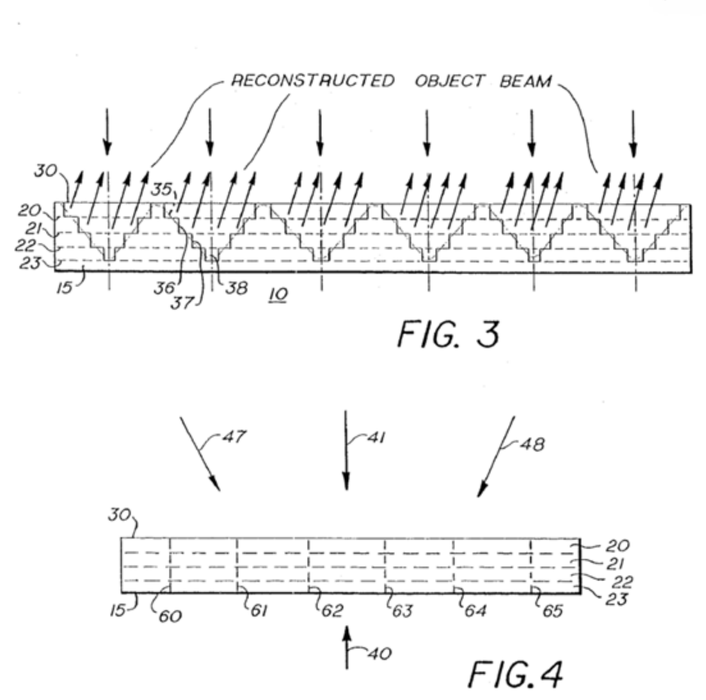
[21] Appl. No.: **204,379**

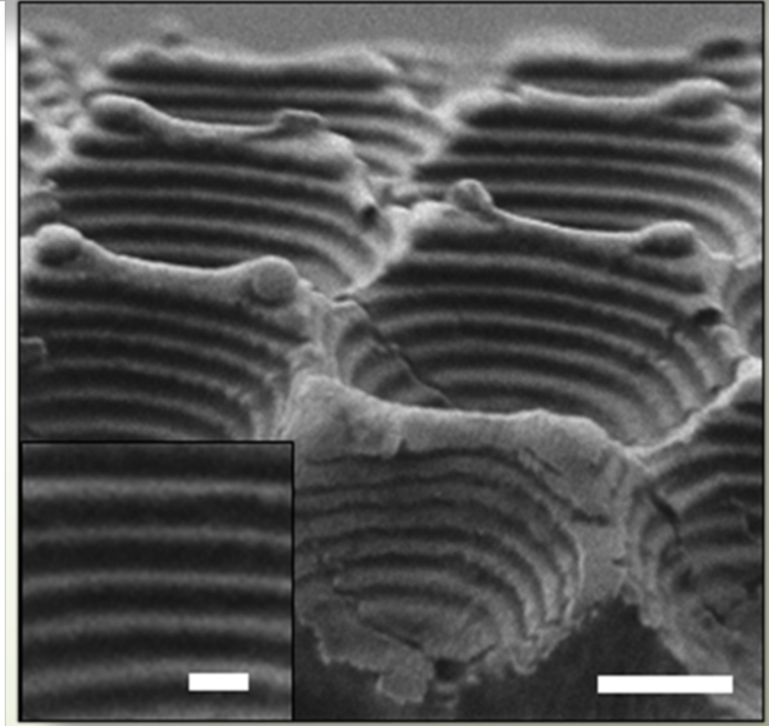
[22] Filed: **Jun. 9, 1988**

by A. R. Neureuther, P. K. Jain & W. G. Oldham, SPIE, vol. 275, Semiconductor Microlithography VI, 1981, pp. 110–115.

"Reduction of Photoresist Standing-Wave Effects by Post-Exposure Bake", by E. D. Walker, IEEE Trans. Elec. Dev., vol. ED-22, No. 7, Jul. 1975, pp. 464–466.

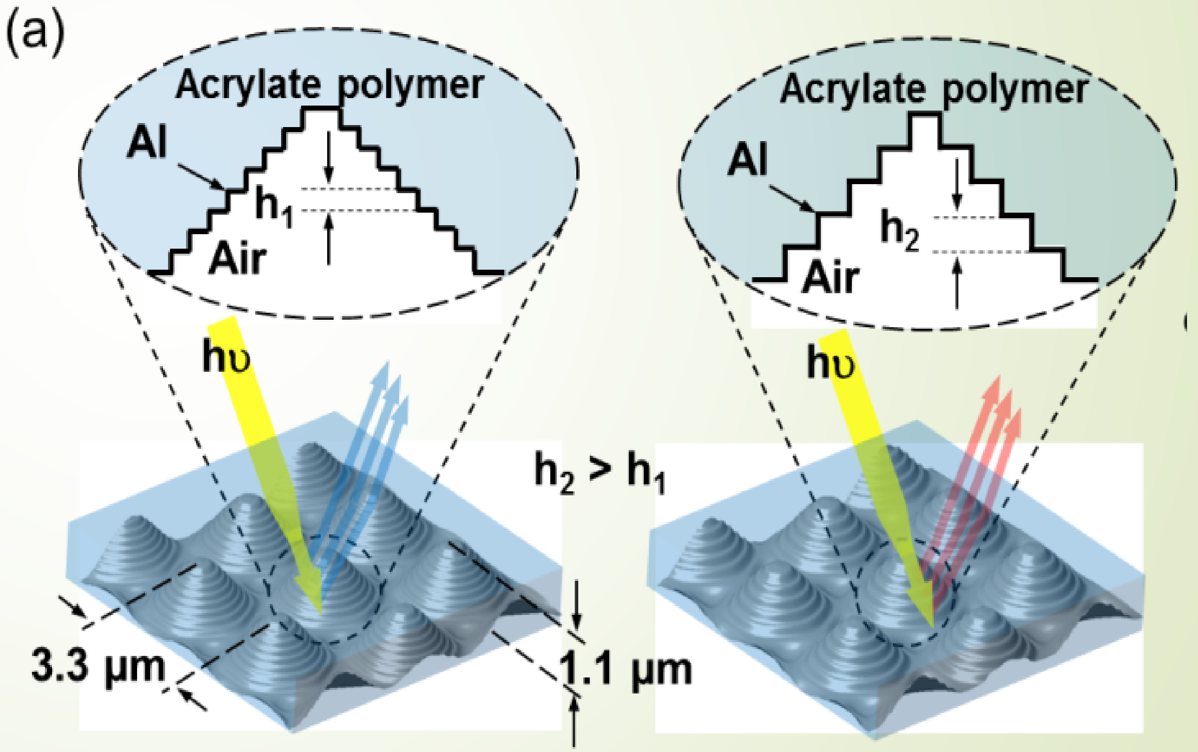
"Projection Printed Photolithographic Images in Positive Photoresists", by M. A. Narasimham, IEEE Trans. Elec. Dev., vol. ED-22, No. 7, Jul. 1975, pp. 478–482.





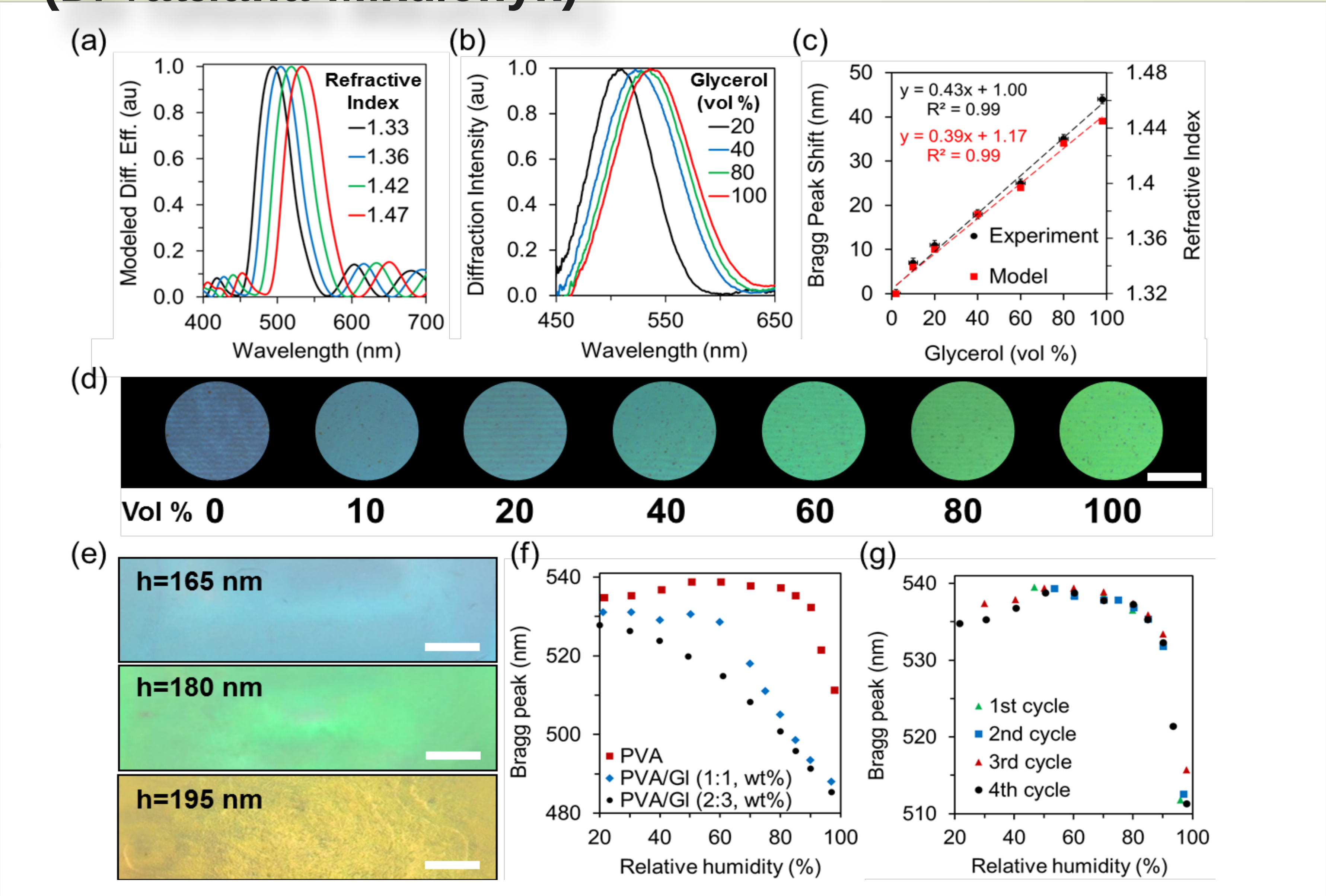
Diffraction from Aztec grating

$$h = \frac{\lambda}{2n\cos\theta}$$



Sensors based on coated Aztec gratings

(Dr Tatsiana Mikulchyk)



Holographic humidity sensors

A visual holographic indicator of relative humidity

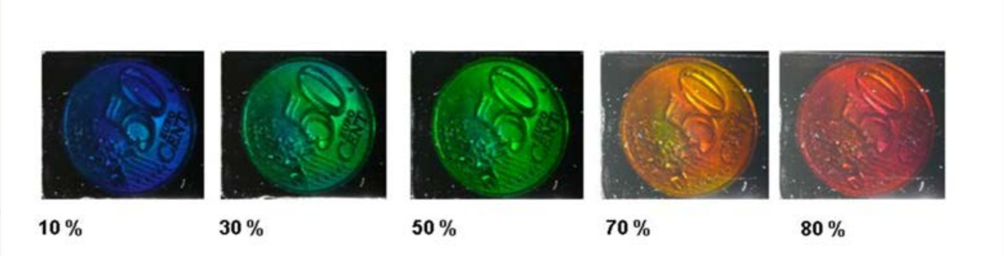


Figure 1. Change of the image colour when a hologram is exposed to different humidity levels.

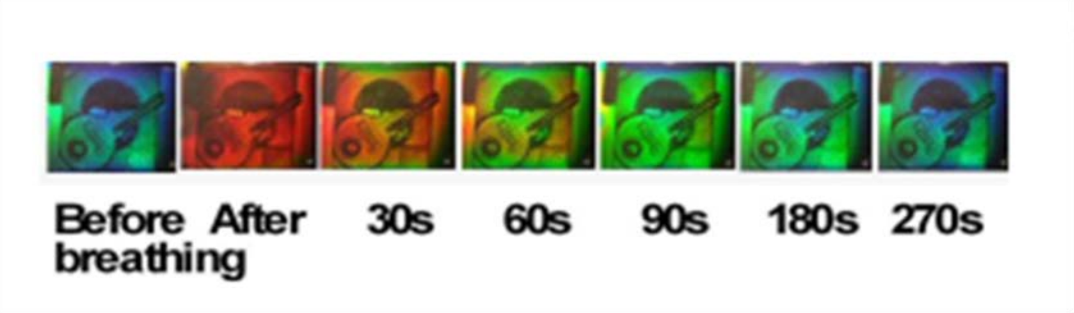
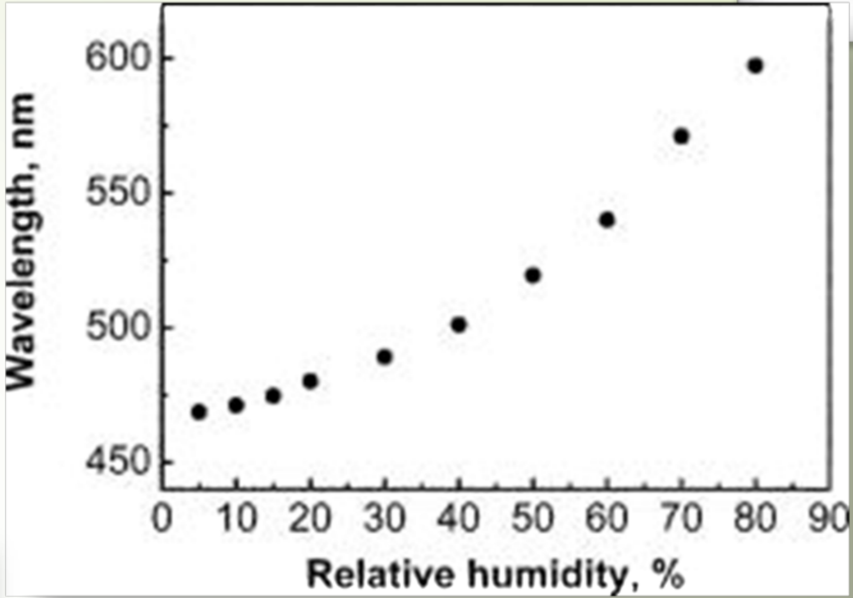


Figure 2. Colour appearance of a reflection hologram before and after breathing on it

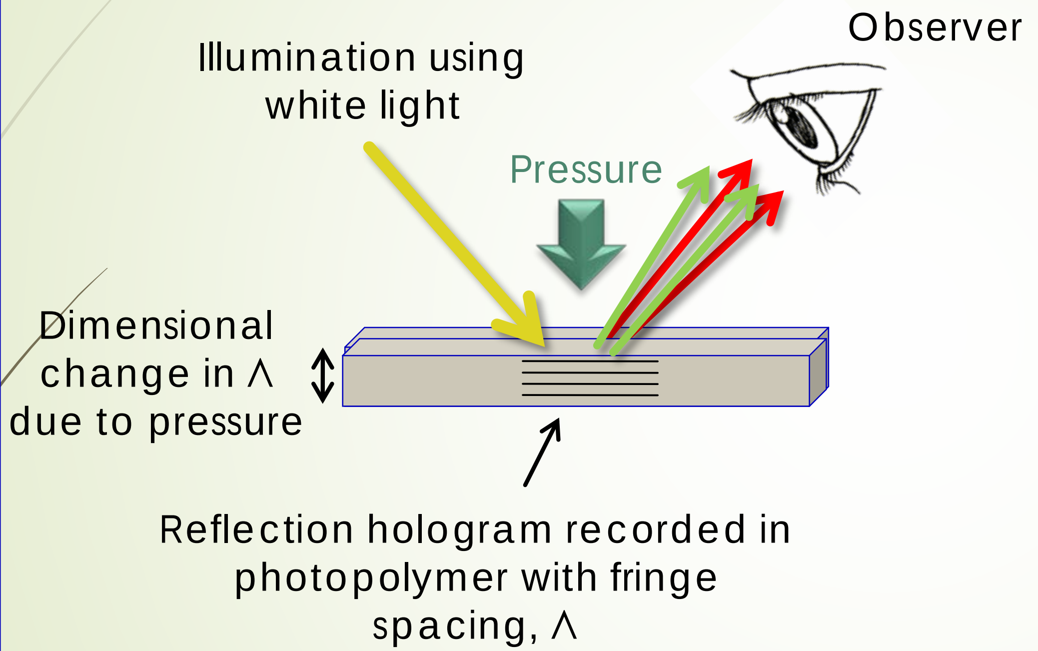


Sensor characteristics	
Recording material	Acrylamide-based photopolymer
Photonic structure	Volume phase reflection grating
Operation range	5 – 80 % RH
Reversibility	Fully reversible
Replay wavelength	400-700 nm

Naydenova I., Jallapuram R., Toal V., Martin S, Applied Physics Letters, **92**, 031109, 2008.

Naydenova I. Jallapuram R., Toal V., Martin S, Sensors and Actuators B: Chemical, **139**, 35, 2009.

Holographic Pressure Sensor



$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta n}{n} + \frac{\Delta\Lambda}{\Lambda} + \cot\theta\,\Delta\theta$$

Pressure Sensor Applications:

- Security and Anti-Counterfeit
- Medical

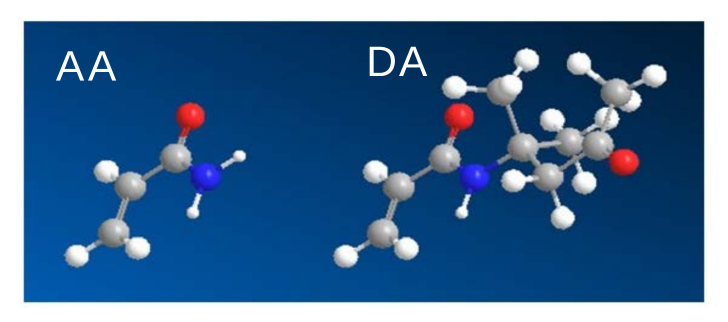
Pressure Sensor Material Requirements:

1. Elastic
2. Low toxicity
3. Readily records bright reflection holograms

Pressure Sensitive Photopolymer (Dr. Dervil Cody)

Acrylamide (AA) → Diacetone Acrylamide (DA)

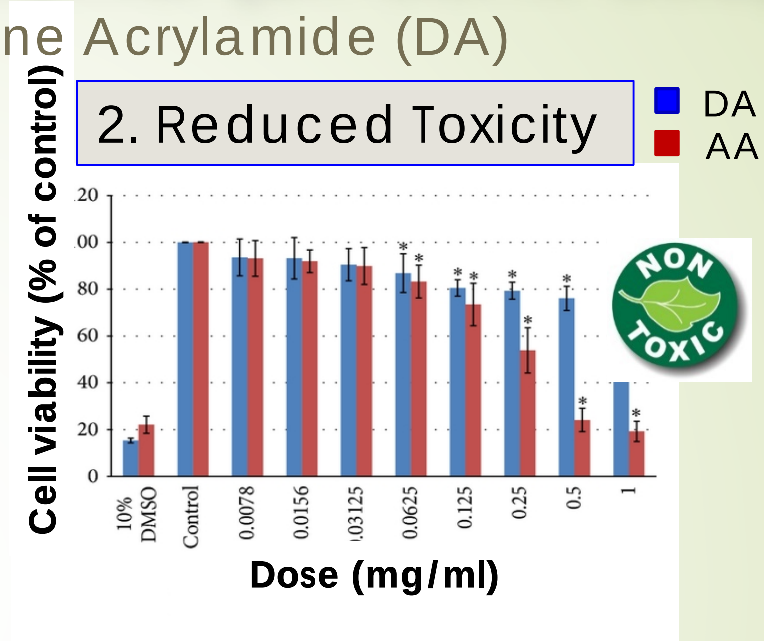
1. Increased Elasticity



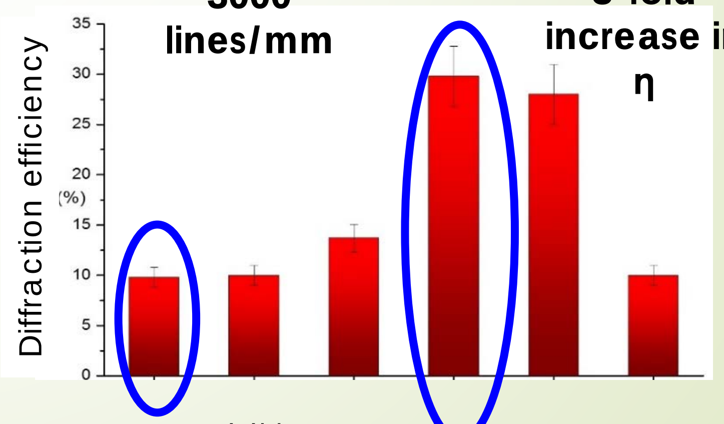
Photopolymer component	*Chemical reagent*
Polymer binder	Polyvinyl Alcohol
Monomer	Diacetone Acrylamide
Cross-linker	*N, N'*-methylene bisacrylamide
Dye	Erythrosin B
Electron donor	Triethanolamine
Plasticizer/Free radical scavanger	Glycerol
Chain Transfer Agent	Citric Acid

D. Cody, S. Gribbin, E. Mihaylova, I. Naydenova., ACS Applied Materials and Interfaces, 2016.

2. Reduced Toxicity



3. Improved Hologram Brightness



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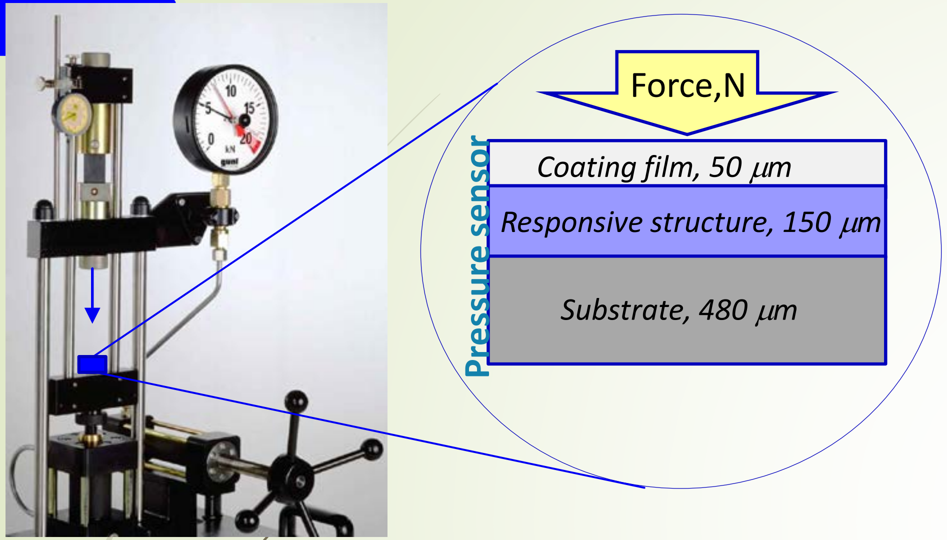
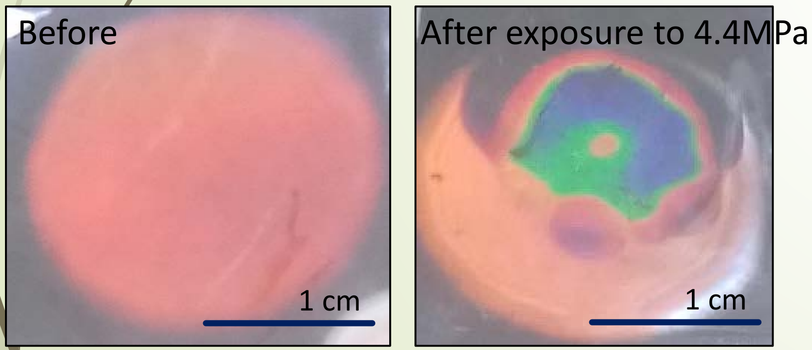
Pressure Response (Dr. Tatsiana Mikulchyk)

Compression with a flat press of 1.25 cm diameter

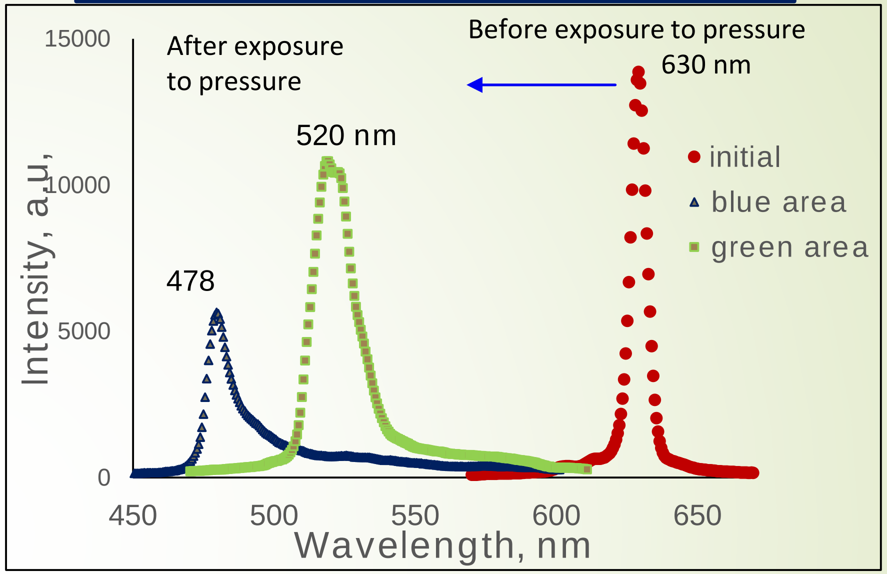


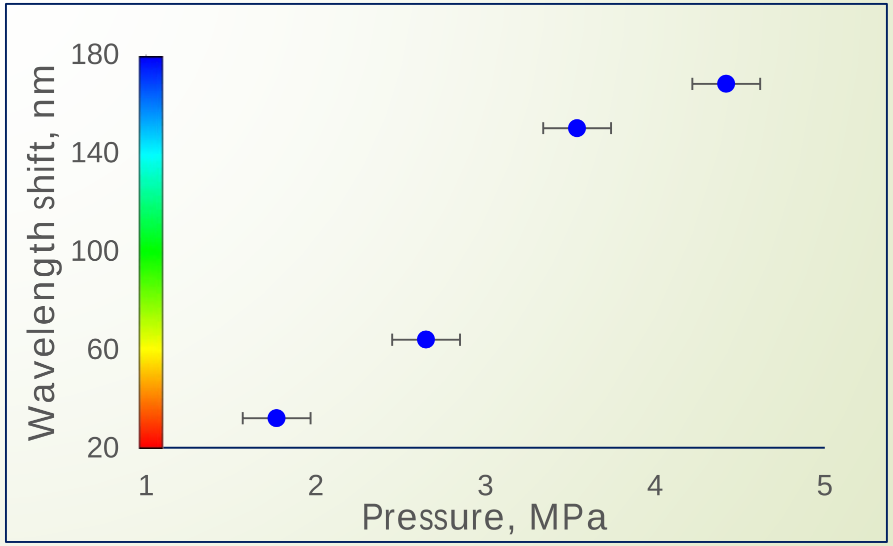
Change of the image colour when a hologram is exposed to pressure



S Martin, V Toal, E Mihaylova, I Naydenova, D Cody
Holographic recording composition, - US Patent 9,927,770, 2018

Blue wavelength shift induced by pressure



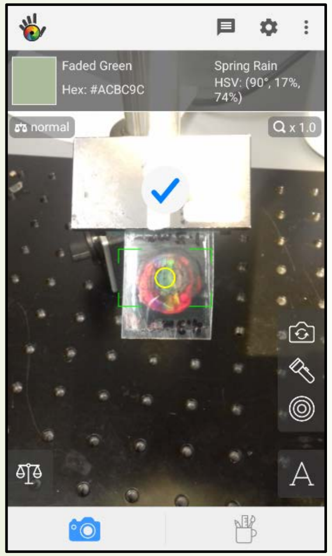


Applied Optics, Vol. 57, No. 22, E173, https://doi.org/10.1364/AO.57.00E173

Possible applications

Pressure indicator

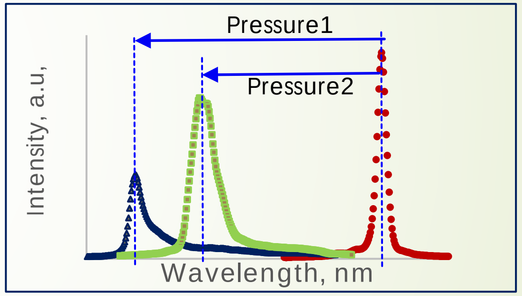
Visual colour change



- correct pressure range → ready to use
- incorrect pressure range → service needed

Pressure calibrator

Wavelength shift



pressure output

- correct pressure range → ready to use
- incorrect pressure range → adjustment needed

Calibration of Ultrasound Systems - https://youtu.be/m2n4wObjV0E

Conclusions

- Functionalised photopolymer holograms are highly versatile sensor platform
- Both colourimetric and electronic read-out are possible. Preliminary theoretical design and selection of the mode of operation are needed. Sensitivity to temperature and humidity must be taken into account.
- Slanted holographic gratings can provide enhanced sensitivity, especially when the layer can swell/shrink.
- Proof of concept sensors/indicators:
    - Temperature
    - VOCs
    - Heavy metals in water
    - Humidity
    - Pressure

Future work

Sensors and actuators

- Integrate sensors in microfluidic devices
- Asymmetric surface photonic structures
- Polarisation holograms

Materials development

Optimisation of the polymer matrices - cellulose and sol-gel (porosity, concentration of functionalising material)

Novel functionalising materials

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