Институт по Оптически Материали и Технологии
“Акад. Йордан Малиновски”
Българска Академия на Науките

Поляризационна холография

Развитие и приложения / Еволюция на идеите

проф. д-р Лиан Неделчев

ПУБЛИЧНА АКАДЕМИЧНА ЛЕКЦИЯ

съгласно чл. 27, ал. 9 от Правилник за условията и реда за придобиване на научни степени и за заемане на академични длъжности в ИОМТ – БАН

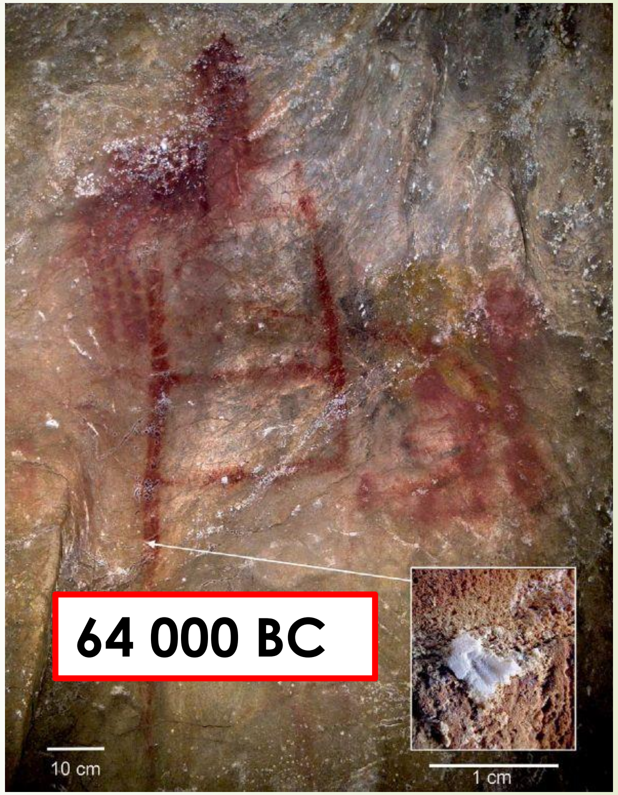
Съдържание

- Исторически преглед
- Изследвания с участие на автора
- Перспективи за бъдещи изследвания

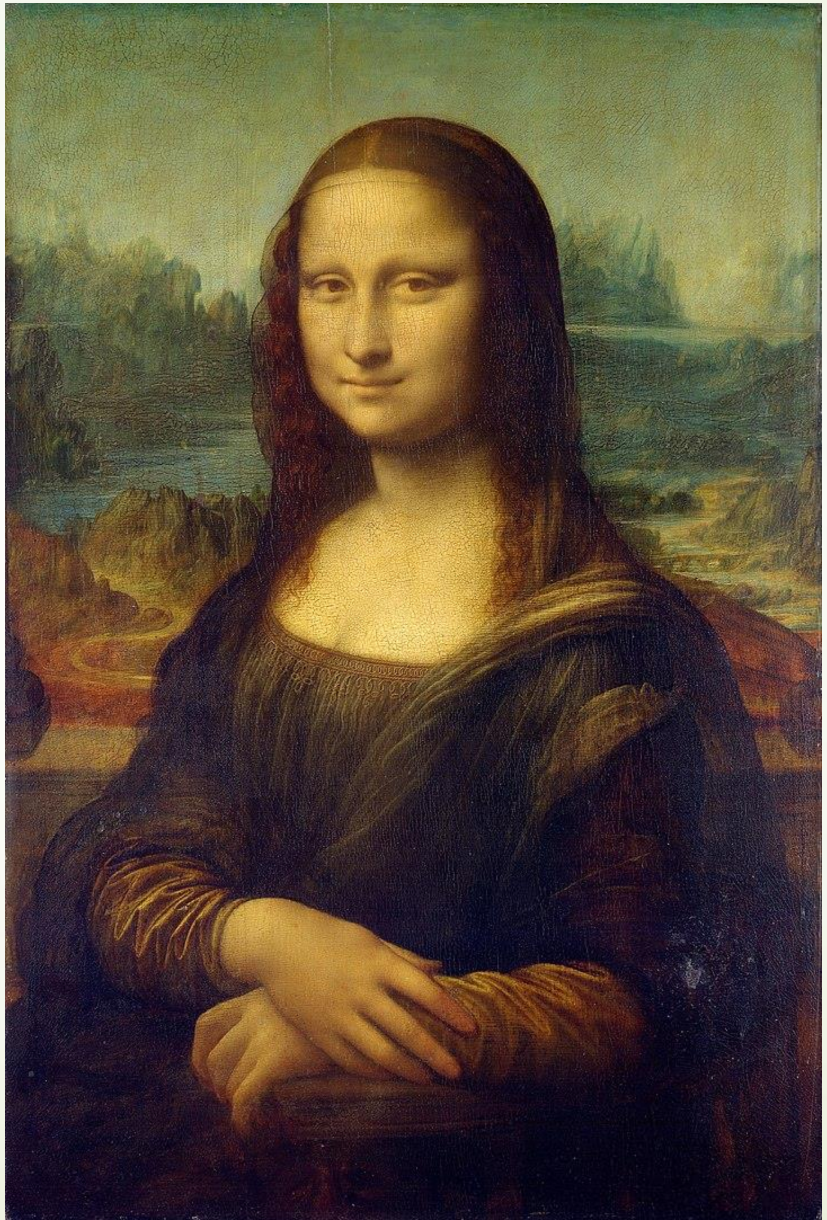
Исторически преглед

Да започнем от началото…

Verba volant, scripta manent
(Казаното отлита, написаното остава)

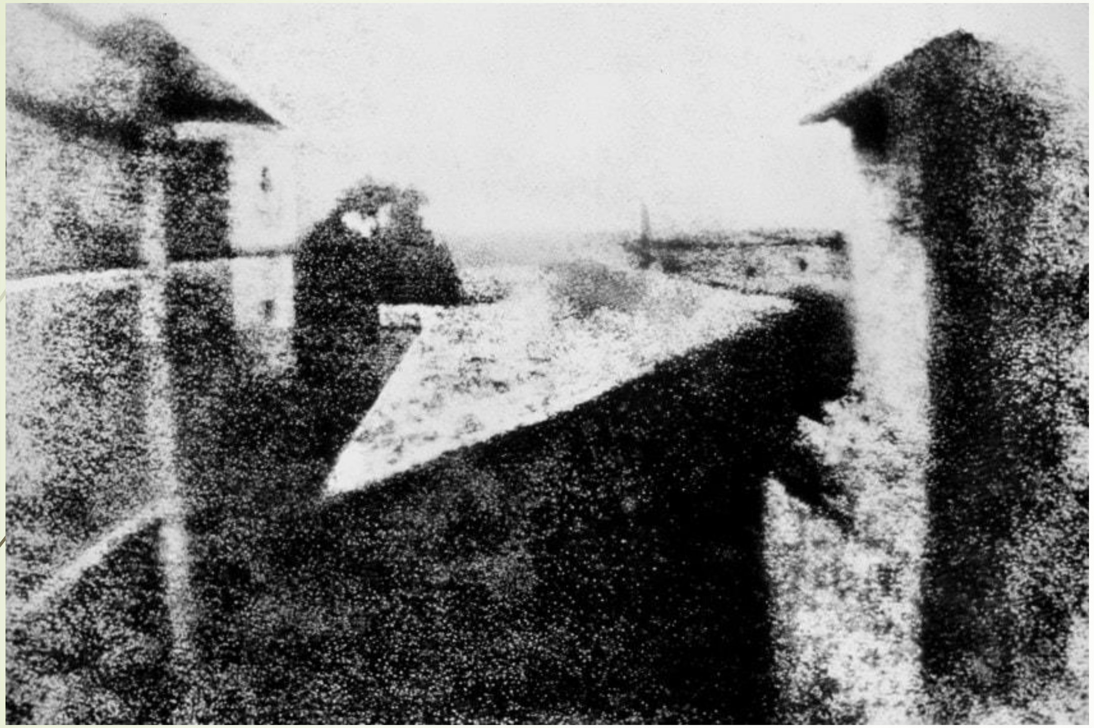


Една картина струва колкото хиляда думи



Mona Lisa / Gioconda
Leonardo da Vinci
1503 - 1506

Фотография

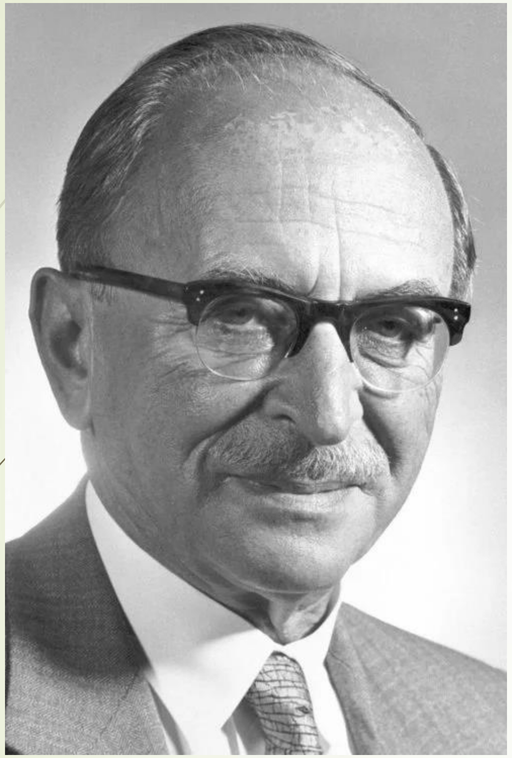


View from the Window at Le Gras
Nicéphore Niépce
1827

Nicéphore Niépce

За разлика от рисуваната картина, фотографията регистрира цялото изображение едновременно! Но… **фото**графията пресъздава само **интензитета** на светлината.

Холография



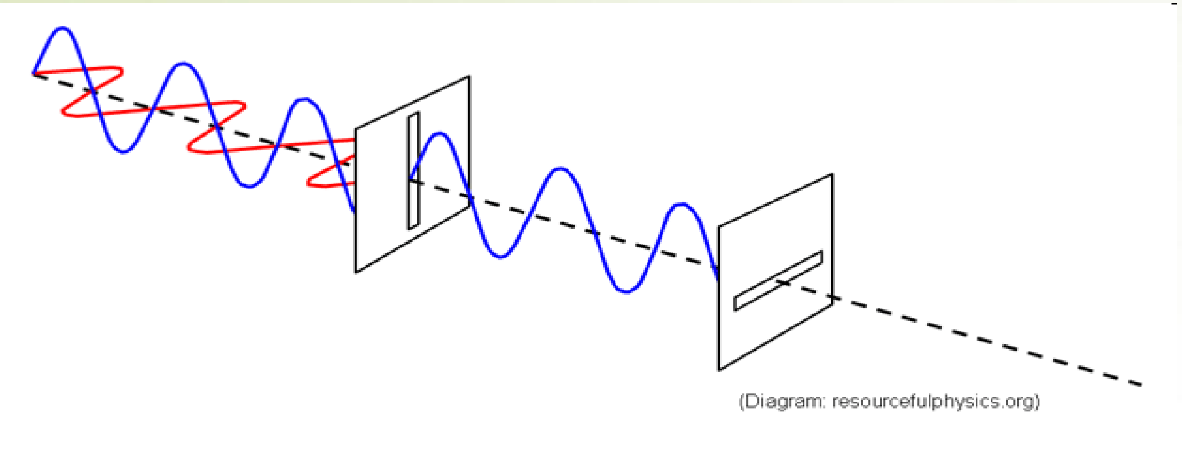
Dennis Gabor
1947 – изобретяване и развитие на холографския метод
1971 – Нобелова награда по Физика

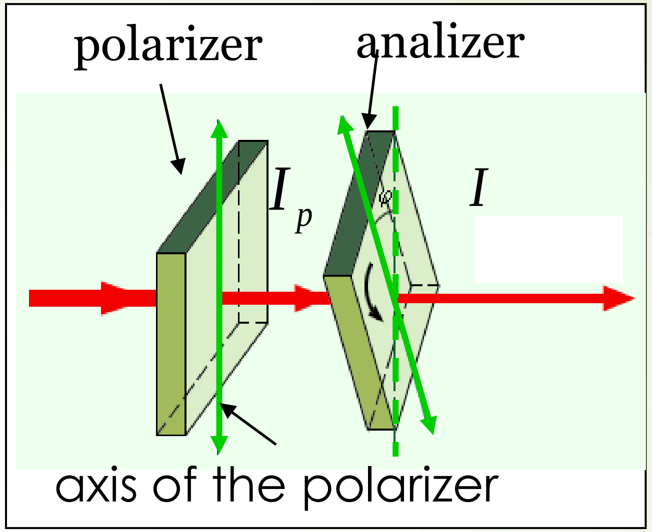
1962 – Първите оптични холограми: Emmett Leith и Juris Upatnieks (USA), Юрий Денисюк (СССР)

Холографията пресъздава не само интензитета, но и фазата на светлината.
Ефекти: дълбочина на сцената, паралакс.

Това ли са наистина **всички** параметри, които характеризират светлинните вълни…?

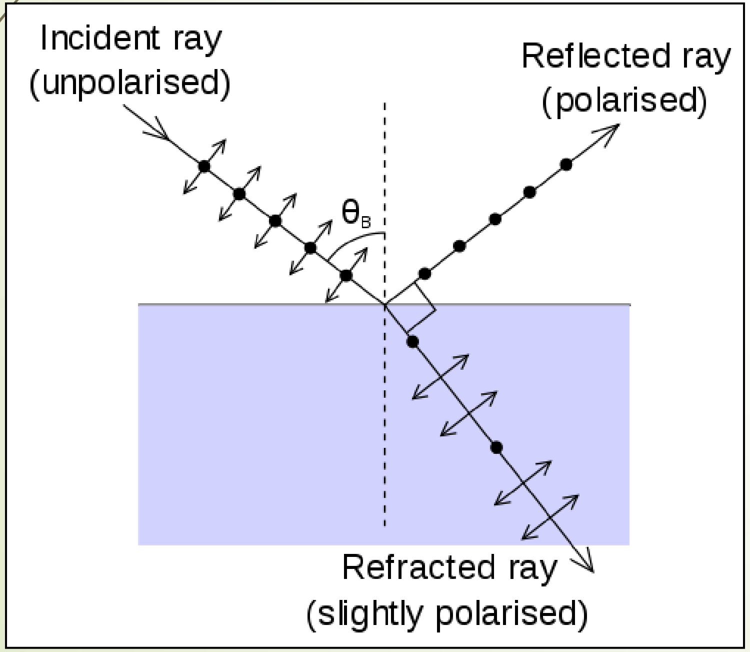
Поляризация





Закон на Малюс

$$\boxed{I = I_p \cos^2 \varphi}$$



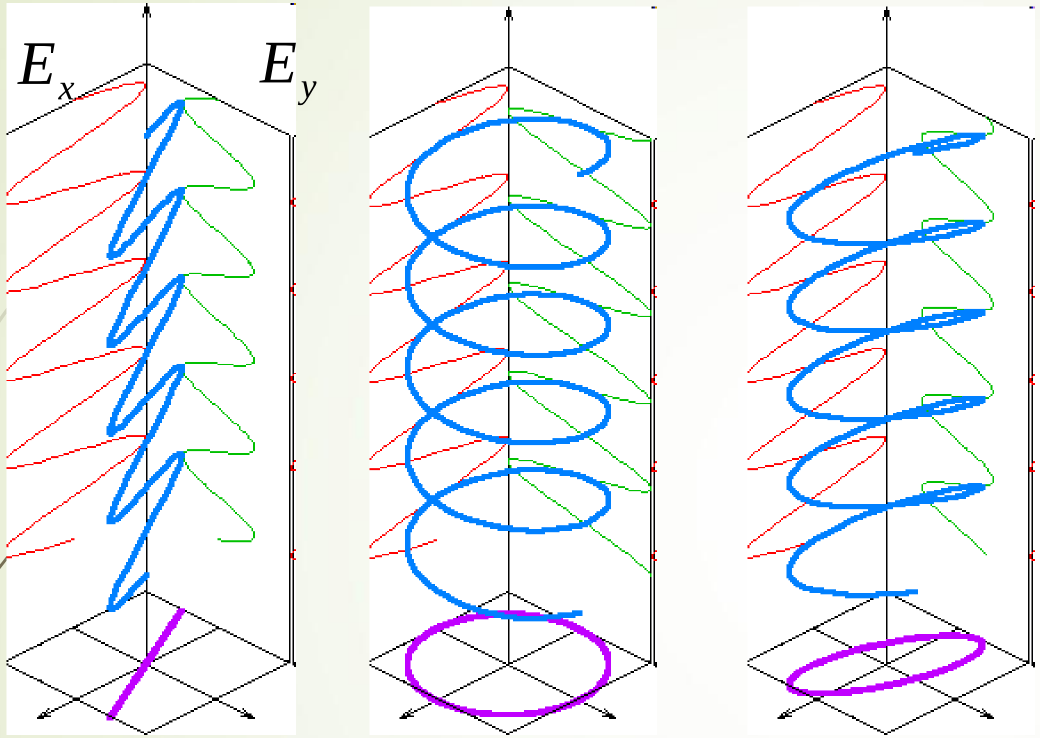
Ъгъл на Брюстер

$$\boxed{\theta_B = \arctan\left(\frac{n_2}{n_1}\right)}$$

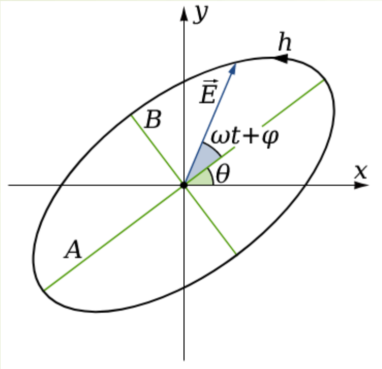
$$\theta_B \approx 53^\circ \; (n_2 = 1.33)$$

$$\theta_B \approx 56^\circ \; (n_2 = 1.5)$$

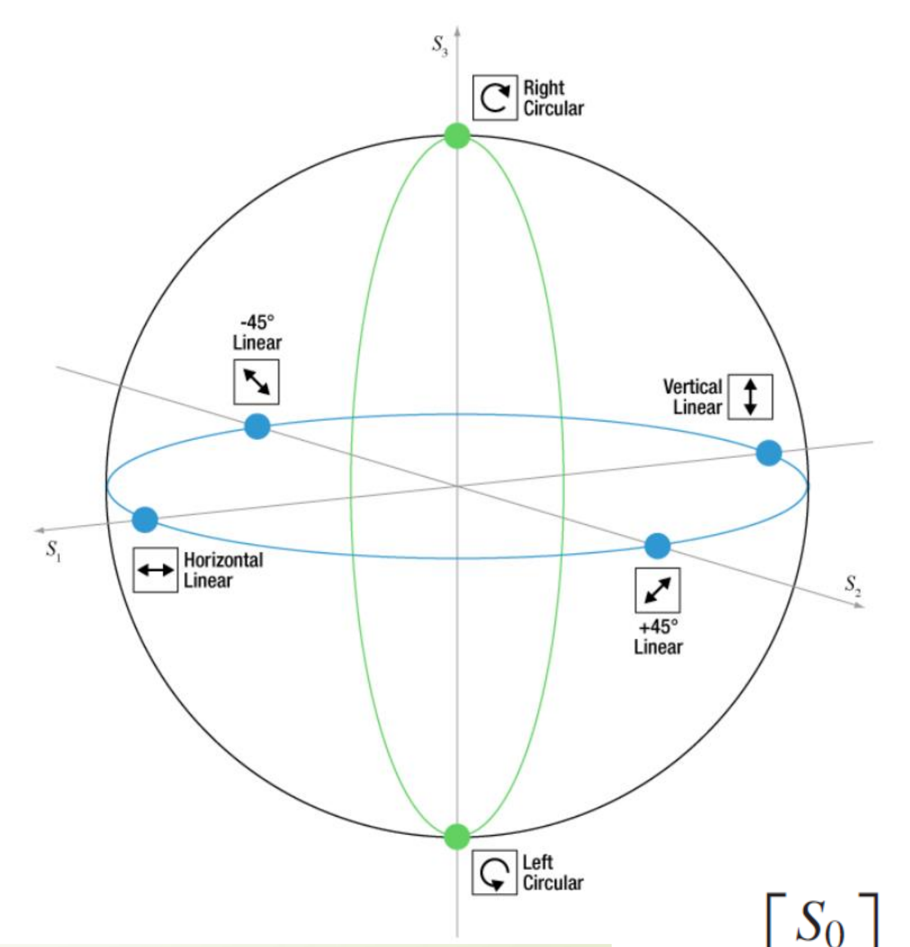
Състояния на поляризация – описание



линейна кръгова елиптична



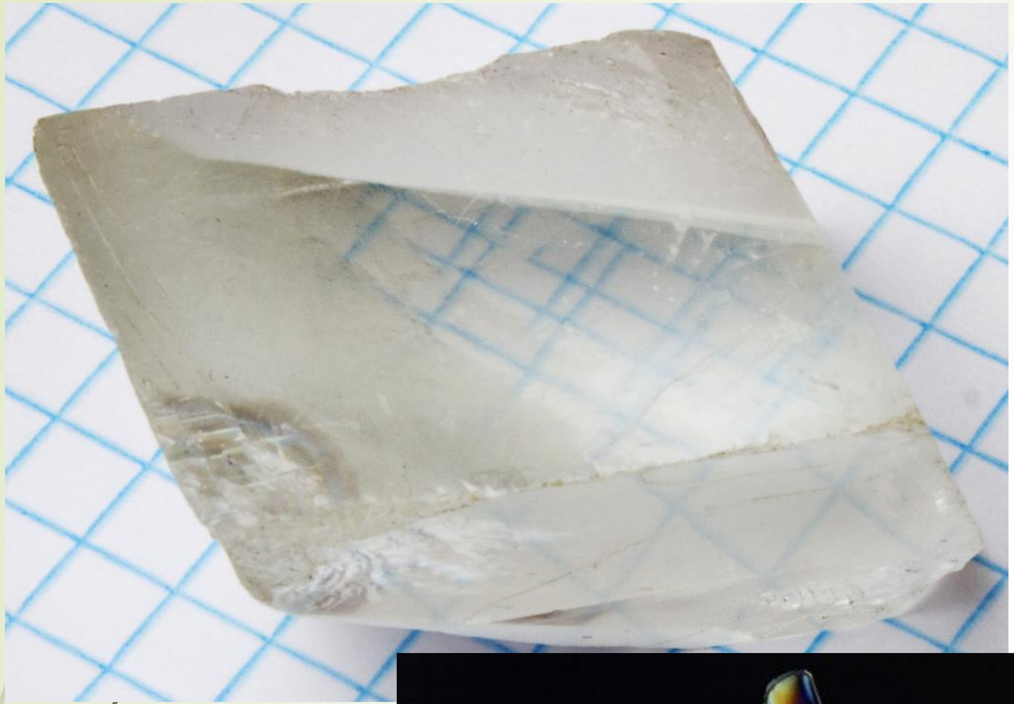
азимут – θ
елиптичност – e
посока – лява/дясна

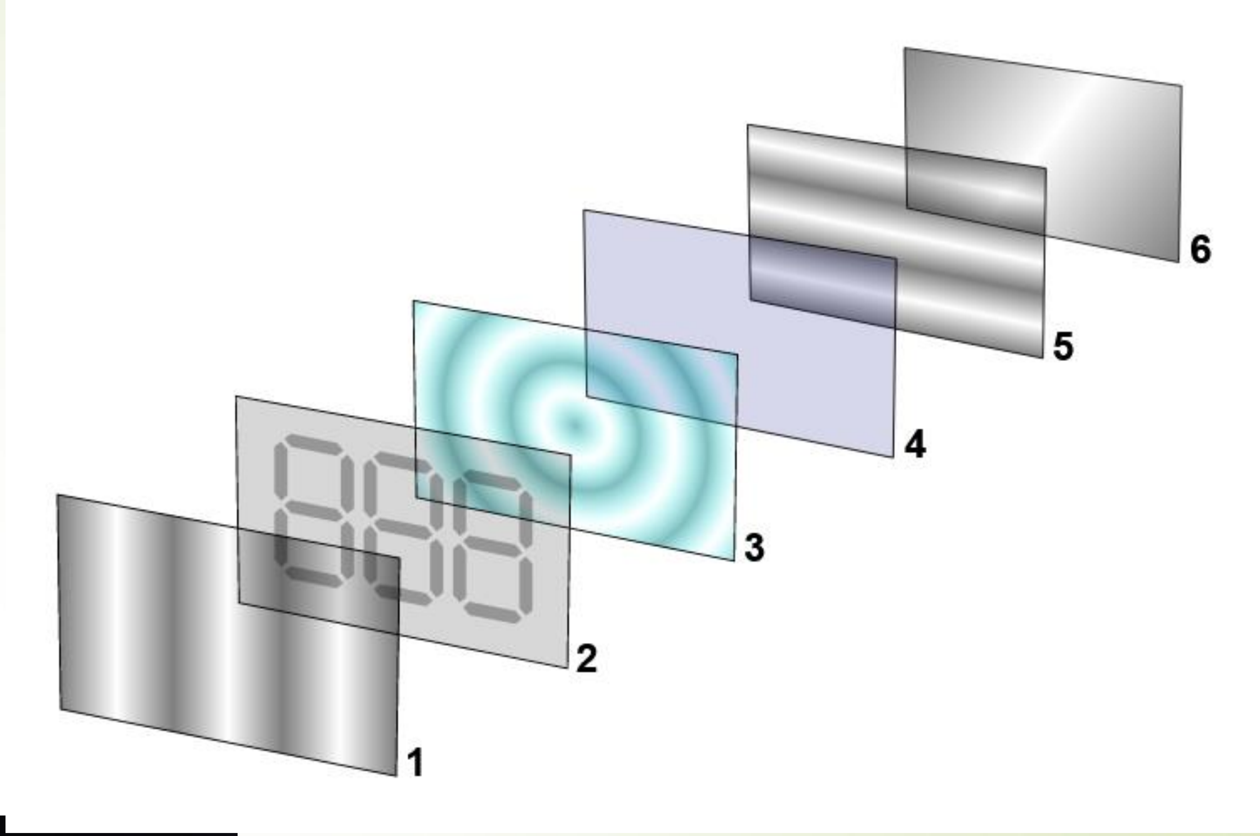


Вектор на Стокс:

$$S = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}$$

Двулъчепречупване





Интерференция на поляризирани вълни

Две вълни с ортогонални линейни поляризации

Две вълни с ортогонални кръгови поляризации

δ – фазова разлика между двете вълни

И в двата показани случая:

- Интензитетът е **константа**;
- Променя се само **поляризацията** на резултантната вълна;

Въпрос:
Как можем да запишем поляризационна холограма в стандартна "чувствителна към интензитета" среда...?

Отговор: ...

НЕ МОЖЕМ!

Поляризационна холография? Само на теория

GENERALIZED THEORY OF INTERFERENCE, AND ITS APPLICATIONS

Part I. Coherent Pencils

BY S. PANCHARATNAM
(*Memoir No. 88 of the Raman Research Institute, Bangalore-6*)

Received October 30, 1956

Reconstruction of Vectorial Wavefronts

A. W. Lohmann

IBM Systems Development Division, Development Laboratory, San Jose, California.
Received 24 May 1965.

Wavefront reconstruction[1] has been aptly termed *holography* which can be translated as *total recording*. The term *total* is used because both the amplitude and the phase of the light wave are recorded, whereas in normal photography, one records only the amplitude. However, at the present time a hologram is not really a total recording, since only one amplitude and one phase are recorded, which would be adequate if light were a scalar wave. The electrical field in the hologram plane contains two vector or polarization components, both with amplitude and phase. We

Ueber das Stickstoffbenzid

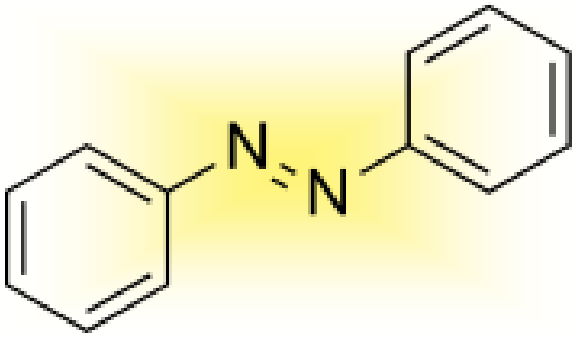
1834

(Poggend. Annalen Bd. XXXI. S. 625.)

Ueber das Stickstoffbenzid;

von Demselben.

Wenn Nitrobenzid (=12C 10H 2N 4O) mit Kalkerde destillirt wird, so wird nur ein höchst unbedeutender Theil davon zersetzt; eine wässerige Kaliauflösung wirkt gleichfalls nur wenig darauf ein, löst man das Kali in Alkohol auf und



Азобензенът е описан за първи път от **Eilhard Mitscherlich**

Stickstoff (DE) = Азот

The *Cis*-form of Azobenzene

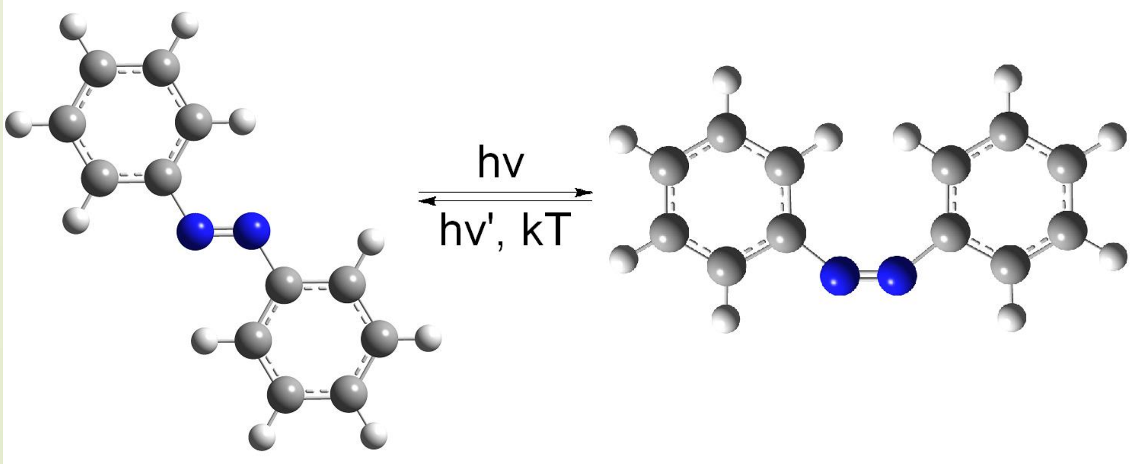
1937

The *Cis*-form of Azobenzene

DURING determinations of the solubility of azobenzene, in which a photometric method of analysis was used, an apparent lack of reproducibility was traced to an increase both in the light absorption of standard solutions and in the concentration of saturated solutions, on exposure to light. The increases reached steady values after several days' exposure in a thermostat tank in a north-lit room. The increase of adsorption was shown to be nearly independent of light intensity, solvent and concentration, but was reached much more rapidly in bright sunlight—a few minutes sufficing for a $M/2000$ solution in a glass bottle. The phenomenon, per-

point, in polar solvents, and smaller solubility in petroleum. Determinations of the dipole moment in benzene solutions, made by Dr. R. J. W. Le Fèvre, give a value of 3·0 Debye units. The apparent moment of the ordinary trans- form increased on exposure of a solution to light from zero to 1·4–1·5 while that of the *cis*-form decreased to the same value. The change indicates that the equilibrium solution contains between 20 and 25 per cent of the *cis*-form, in good agreement with an approximate estimate of 21 per cent by the photometric method, this value, in a *c.* 1 per cent solution in benzene, being somewhat lower than that, 27 per cent, found in much more dilute solution in acetone.

G. S. HARTLEY.



Откриване на ***trans – cis* фотоизомеризацията** на азобензена

G. S. Hartley, "The cis form of azobenzene", *Nature*, **140**, 281 (1937)

Високоефективен фотоанизотропен материал!

1984

Polarization holography. 1: A new high-efficiency organic material with reversible photoinduced birefringence

T. Todorov, L. Nikolova, and N. Tomova

POLARIZATION HOLOGRAPHY .1. A NEW HIGH-EFFICIENCY ORGANIC MATERIAL WITH REVERSIBLE PHOTOINDUCED BIREFRINGENCE

TODOROV, T; NIKOLOVA, L and TOMOVA, N

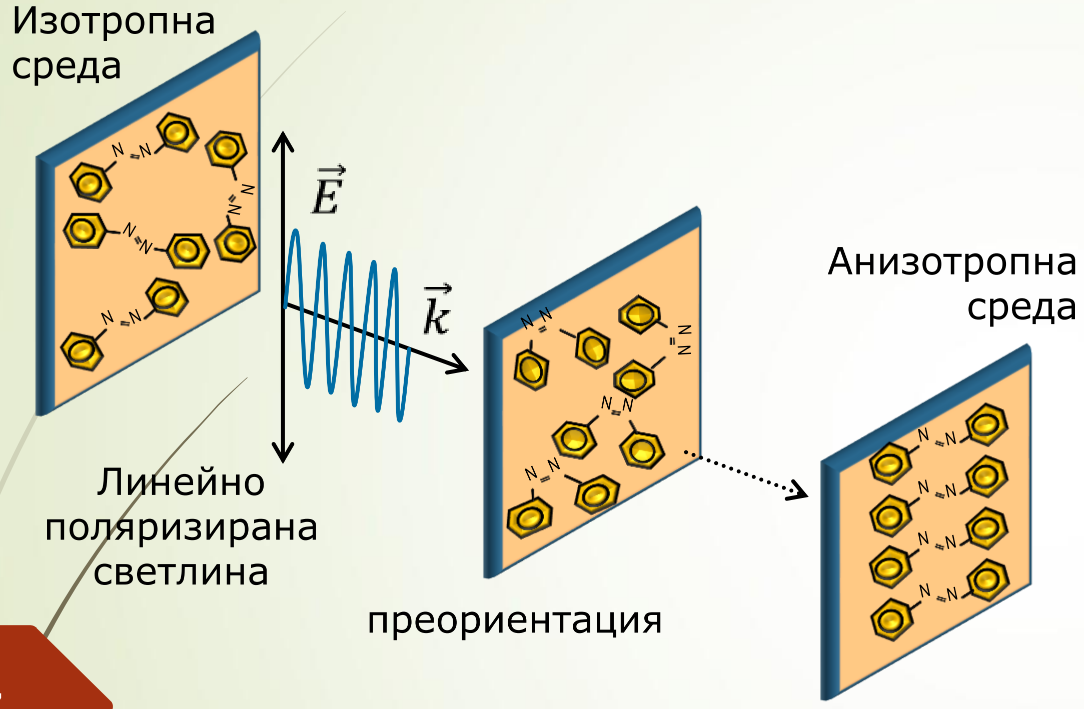
1984 | APPLIED OPTICS 23 (23) , pp.4309-4312

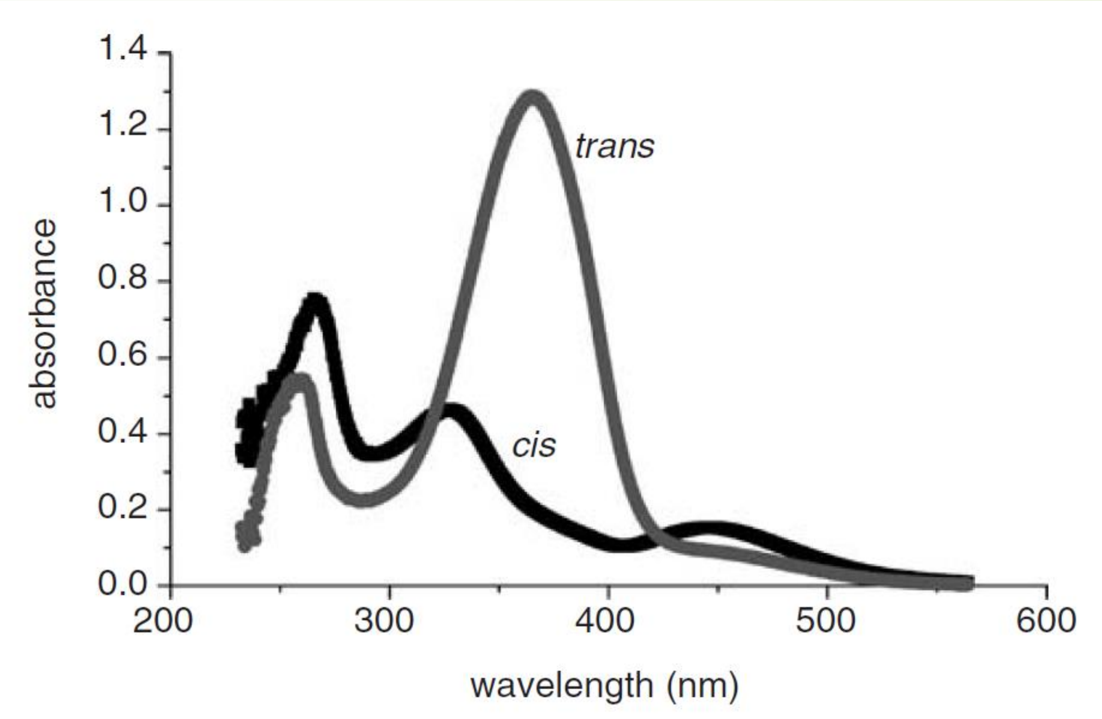
9 от тези цитирания са от 2022 година!

- азобагрило **метилоранж** в поливинил алкохол;
- фотоиндуцирано двулъчепречупване: $\Delta n > 10^{-3}$;
- дифракционна ефективност: $\eta > 35\%$

Todorov *et al*, *Applied Optics* **23**, 4309 (1984).

Механизъм на поляризационния запис

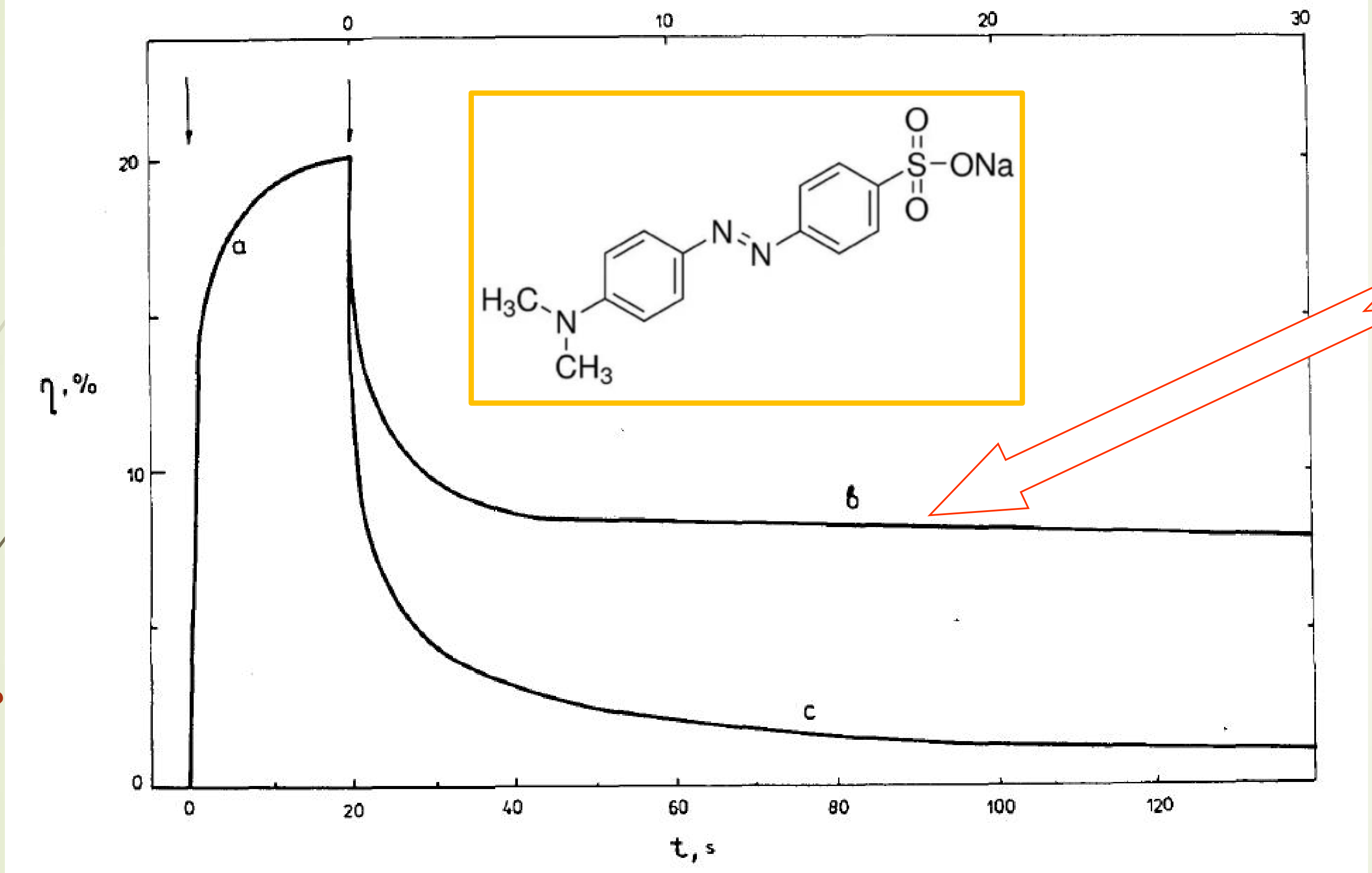




Молекулите преминават през поредица от *транс-цис-транс* изомеризации, докато се **преориентират** перпендикулярно на поляризацията на светлината.
(при **кратко** време на живот на цис състоянието)

Reorientation vs. Angular Hole Burning mechanism
(при **дълго** време на живот на цис състоянието)

От азобагрила към азополимери



Недостатък:
Ниска стабилност

Решение:
азополимери

От азобагрила към азополимери

1987

Makromol. Chem., Rapid Commun. **8**, *59 – 63 (1987)* 59

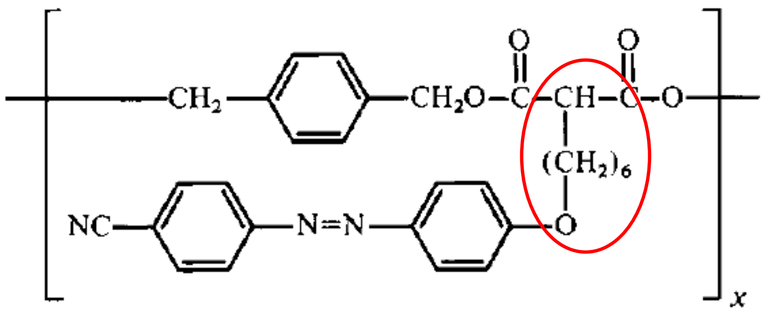
Reversible digital and holographic optical storage in polymeric liquid crystals

*Manfred Eich, Joachim H. Wendorff**

Deutsches Kunststoff-Institut, Schloßgartenstraße 6R, D-6100 Darmstadt, FRG

Bernd Reck, Helmut Ringsdorf

Institut für Organische Chemie, Joh. Gu
J. J. Becher-Weg 18 – 20, D-6500 Mainz

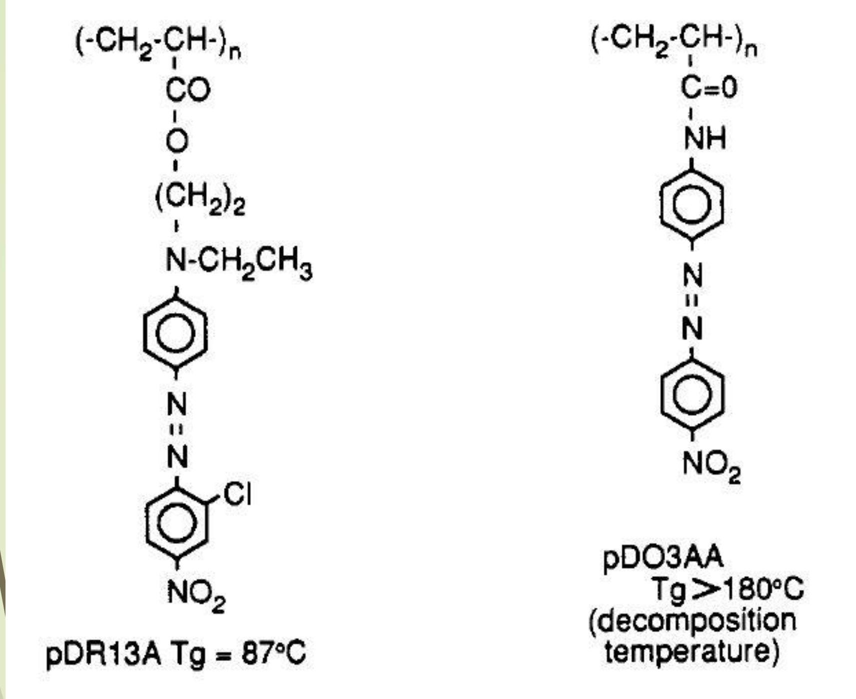


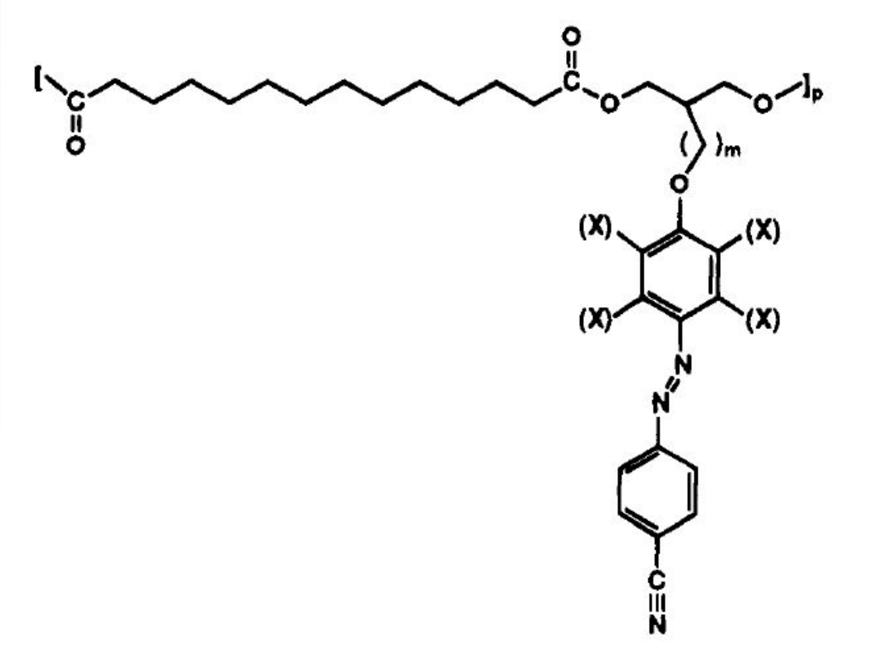
g 43 s_A 94 n 104 i

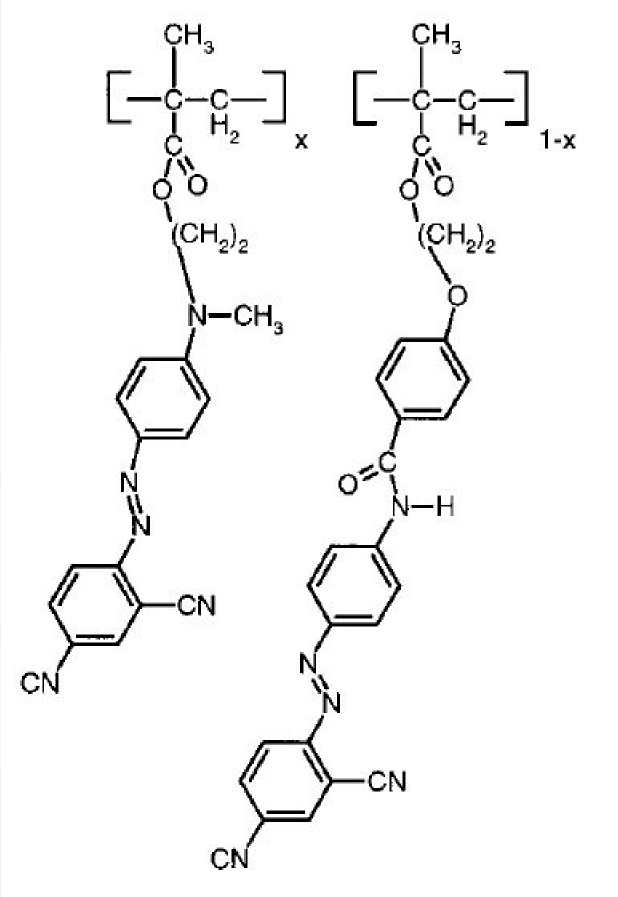
1

При азополимерите азохромофорът е химически свързан към полимерната верига

В търсене на идеалния азополимер…

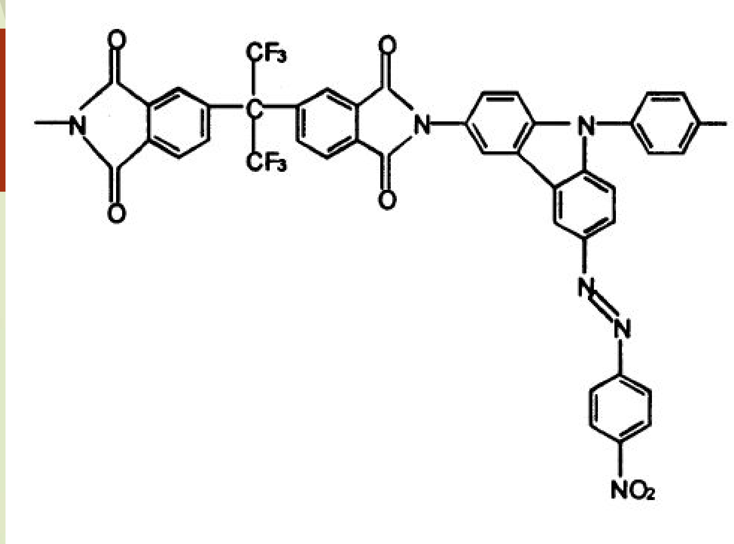


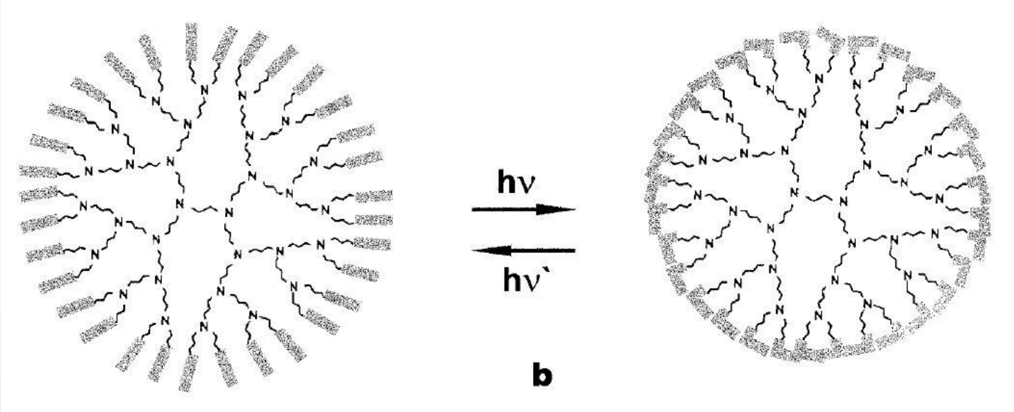




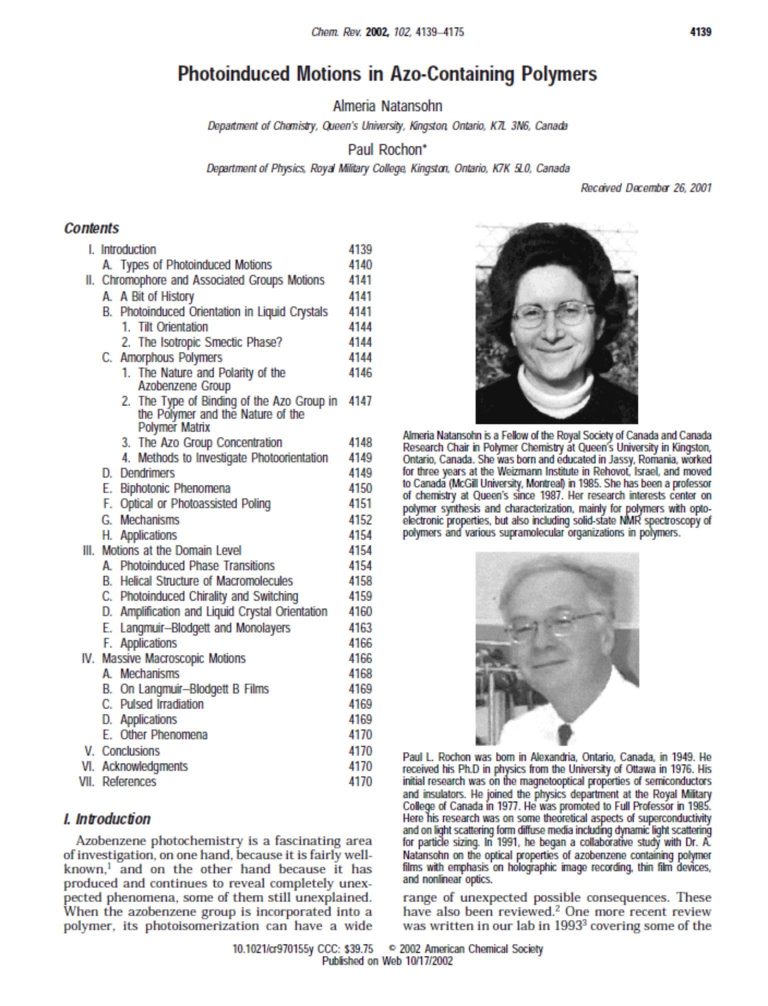
x=40%, **Δn=0.23**

Adv. Mater. **10**, 855–859 (1998)





Ключови обзори в областта



Chem. Rev. **2002,** *102,* 4139–4175 4139

Photoinduced Motions in Azo-Containing Polymers

Almeria Natansohn
Department of Chemistry, Queen's University, Kingston, Ontario, K7L 3N6, Canada
Paul Rochon*
Department of Physics, Royal Military College, Kingston, Ontario, K7K 5L0, Canada

Received December 26, 2001

Contents

I. Introduction

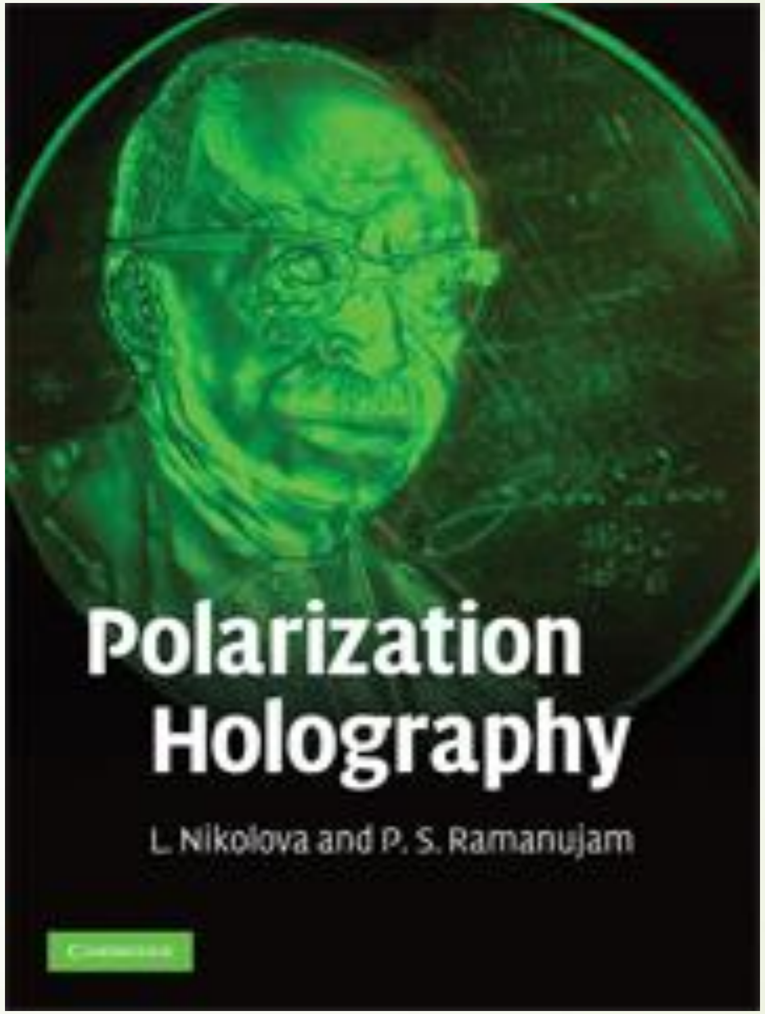
Azobenzene photochemistry is a fascinating area of investigation, on one hand, because it is fairly well-known,[1] and on the other hand because it has produced and continues to reveal completely unexpected phenomena, some of them still unexplained. When the azobenzene group is incorporated into a polymer, its photoisomerization can have a wide range of unexpected possible consequences. These have also been reviewed.[2] One more recent review was written in our lab in 1993[3] covering some of the

Almeria Natansohn is a Fellow of the Royal Society of Canada and Canada Research Chair in Polymer Chemistry at Queen's University in Kingston, Ontario, Canada. She was born and educated in Jassy, Romania, worked for three years at the Weizmann Institute in Rehovot, Israel, and moved to Canada (McGill University, Montreal) in 1985. She has been a professor of chemistry at Queen's since 1987. Her research interests center on polymer synthesis and characterization, mainly for polymers with opto-electronic properties, but also including solid-state NMR spectroscopy of polymers and various supramolecular organizations in polymers.

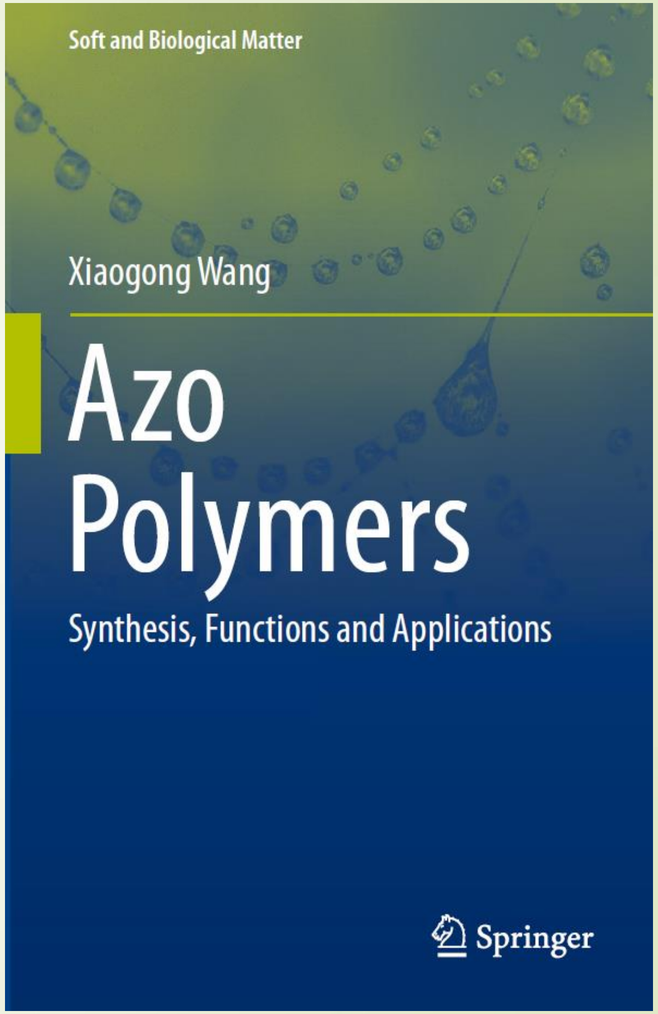
Paul L. Rochon was born in Alexandria, Ontario, Canada, in 1949. He received his Ph.D in physics from the University of Ottawa in 1976. His initial research was on the magnetooptical properties of semiconductors and insulators. He joined the physics department at the Royal Military College of Canada in 1977. He was promoted to Full Professor in 1985. Here his research was on some theoretical aspects of superconductivity and on light scattering form diffuse media including dynamic light scattering for particle sizing. In 1991, he began a collaborative study with Dr. A. Natansohn on the optical properties of azobenzene containing polymer films with emphasis on holographic image recording, thin film devices, and nonlinear optics.

10.1021/cr970155y CCC: $39.75
Published on Web 10/17/2002

Chemical Reviews **102**, 4139 (2002)



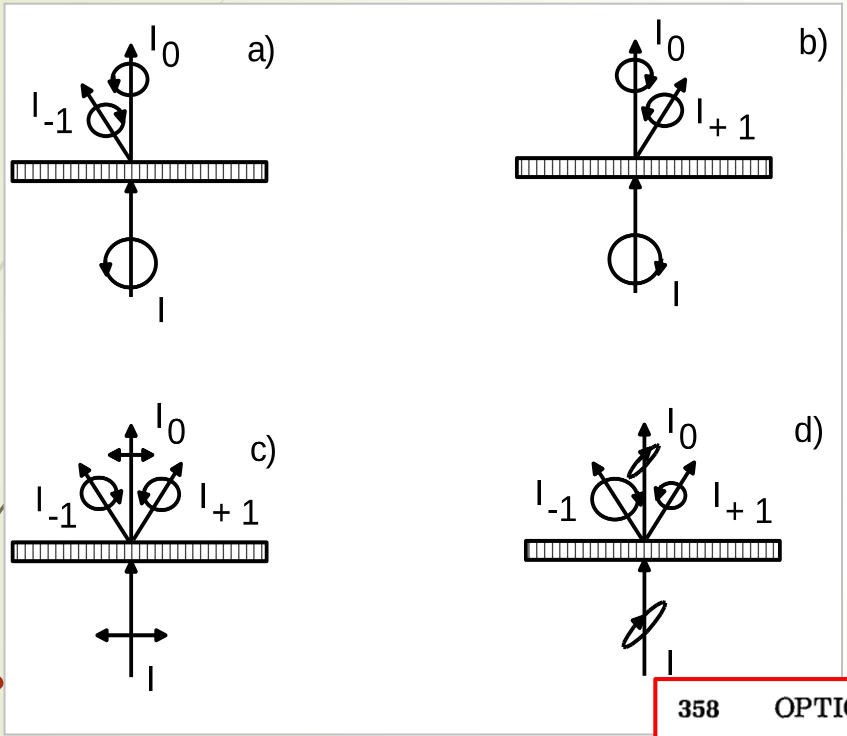
Polarization holography (2009)



Azo polymers (2017)

Кръговополяризационен светоделител с приложение за спектрофотополяриметър

1992



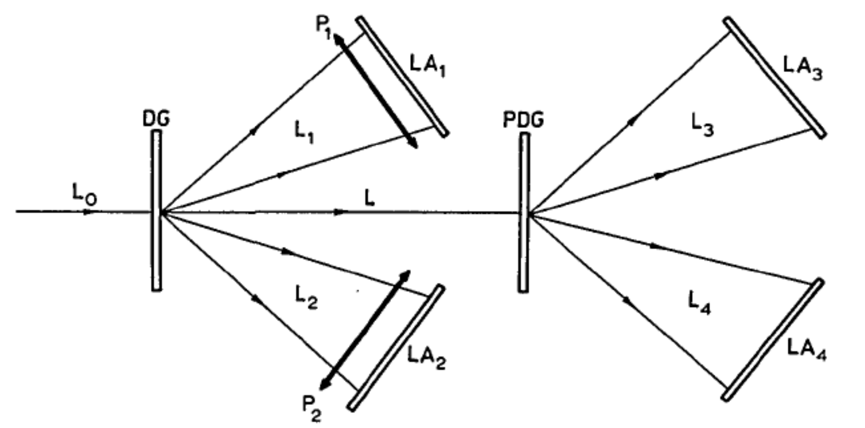


Fig. 1. Optical scheme of the proposed spectrophotopolarimeter. DG, diffraction grating; PDG, polarization diffraction grating; P_1 and P_2, linear polarizers; LA_1, LA_2, LA_3, and LA_4, linear photoarrays.

358 OPTICS LETTERS / Vol. 17, No. 5 / March 1, 1992

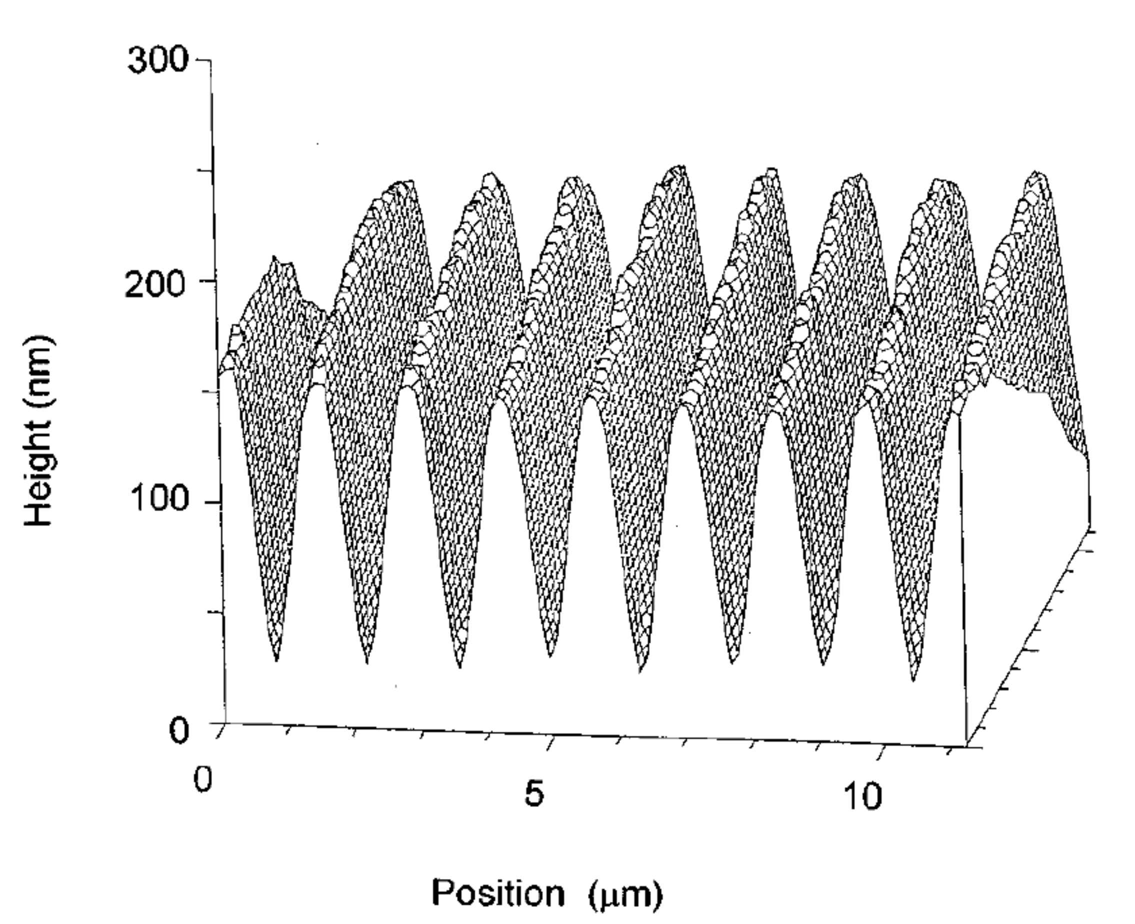
Spectrophotopolarimeter: fast simultaneous real-time measurement of light parameters

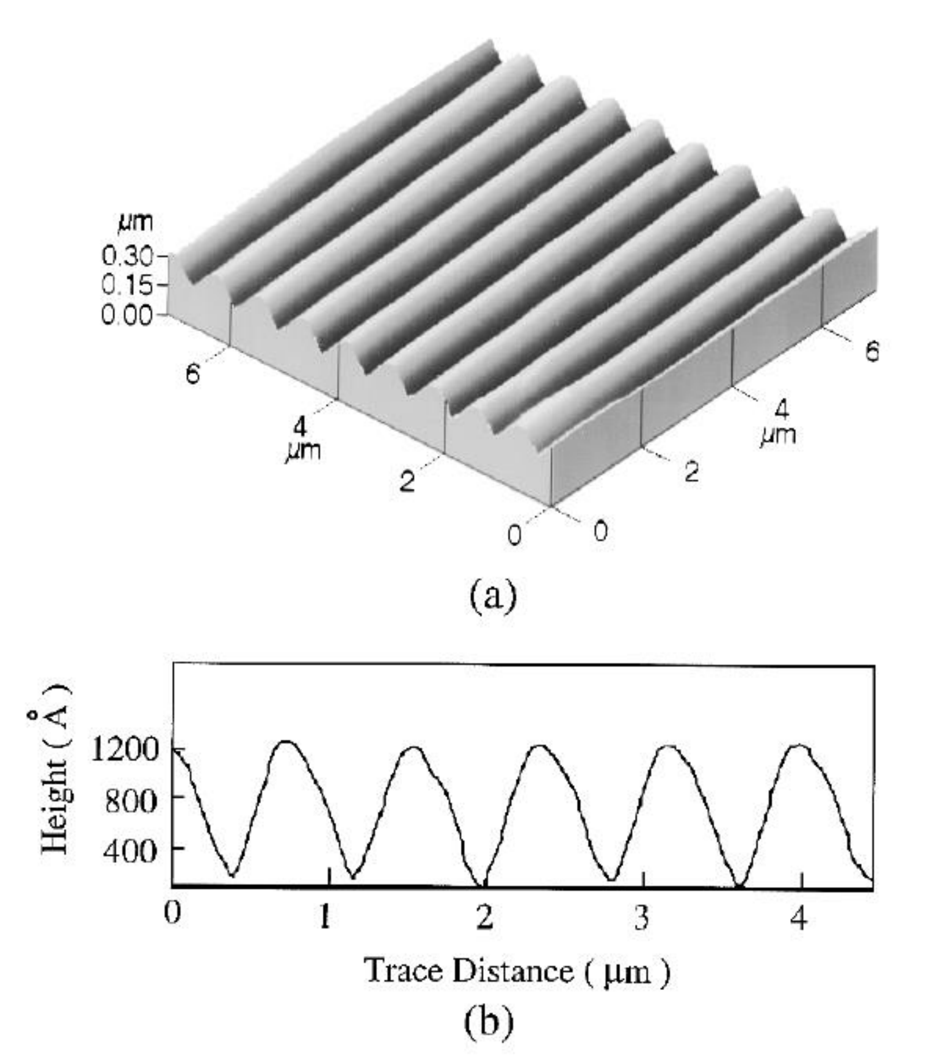
T. Todorov and L. Nikolova

Central Laboratory of Optical Storage and Processing of Information, Bulgarian Academy of Sciences, P.O. Box 95, Sofia 1113, Bulgaria

Повърхностен релеф в азополимери (SRG)

1995





Повърхностният релеф: едно „едновременно“ откритие

Optically induced surface gratings on azoaromatic polymer films

P. Rochon and E. Batalla
Department of Physics, Royal Military College, Kingston, Ontario K7K 5L0, Canada

A. Natansohn
Department of Chemistry, Queen's University, Kingston, Ontario K7L 3N6, Canada

(Received 15 August 1994; accepted for publication 1 November 1994)

Laser-induced holographic surface relief gratings on nonlinear optical polymer films

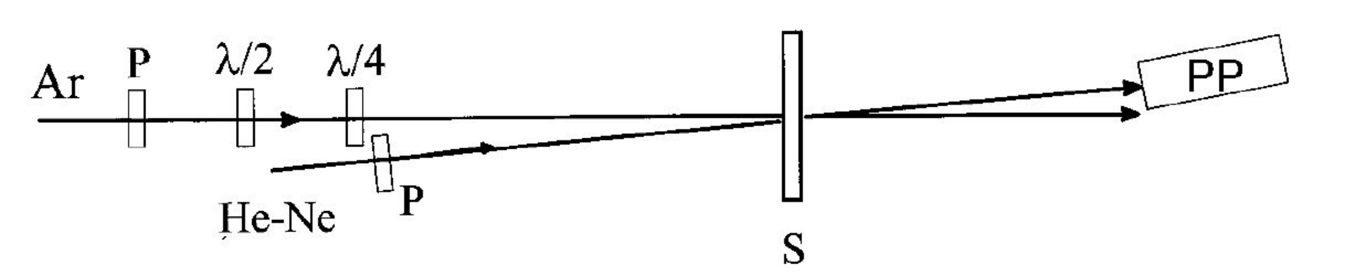
D. Y. Kim and S. K. Tripathy
Center for Advanced Materials, Department of Chemistry, University of Massachusetts Lowell, Lowell, Massachusetts 01854

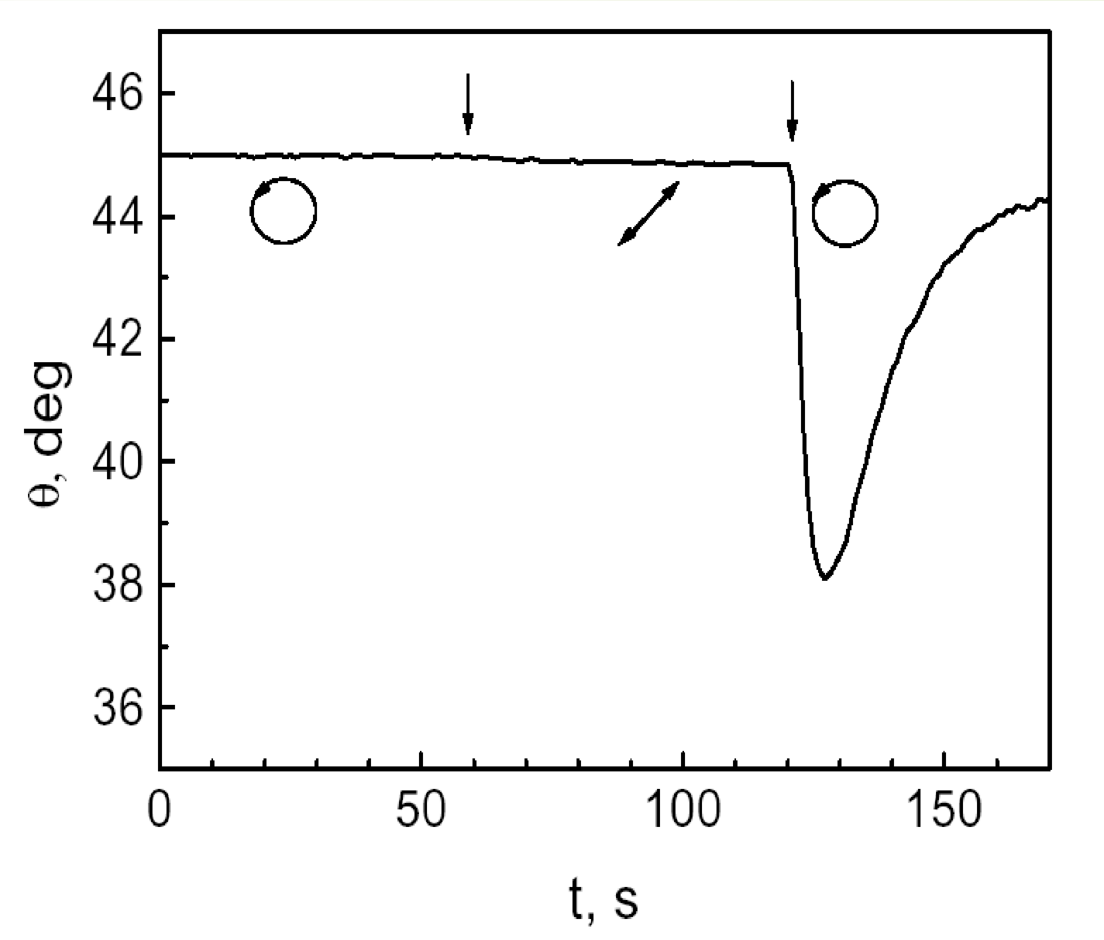
Lian Li and J. Kumar
Center for Advanced Materials, Department of Physics, University of Massachusetts Lowell, Lowell, Massachusetts 01854

(Received 14 September 1994; accepted for publication 20 December 1994)

Кръгова анизотропия в азополимери

2000





Еволюция на азимута на пробния лъч θ ($\theta_0 = 45°$). Стрелките указват смяната на поляризацията на възбуждащия аргонов лъч.

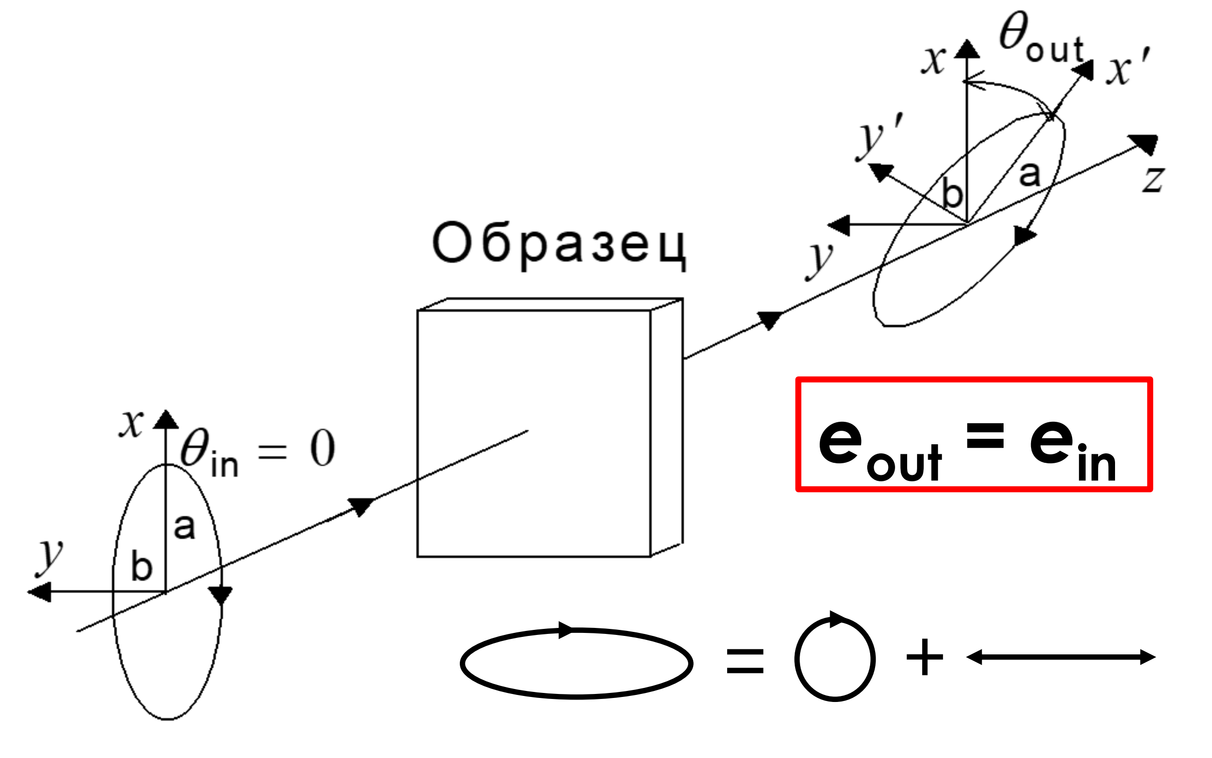
M. Ivanov, I. Naydenova, T. Todorov, L. Nikolova, T. Petrova, N. Tomova, and V. Dragostinova, "Light-induced optical activity in optically ordered amorphous side-chain azobenzene containing polymer," J. Mod. Opt. **47**, 861–867 (2000)

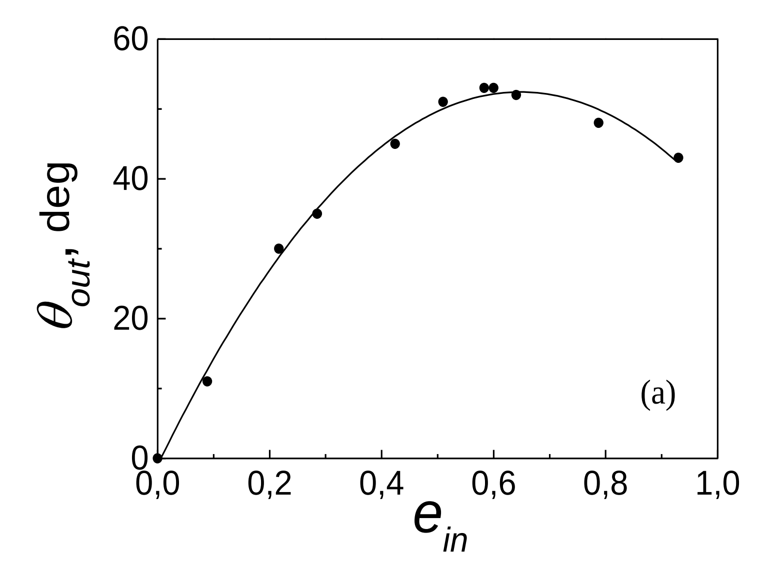
Изследвания с участие на автора

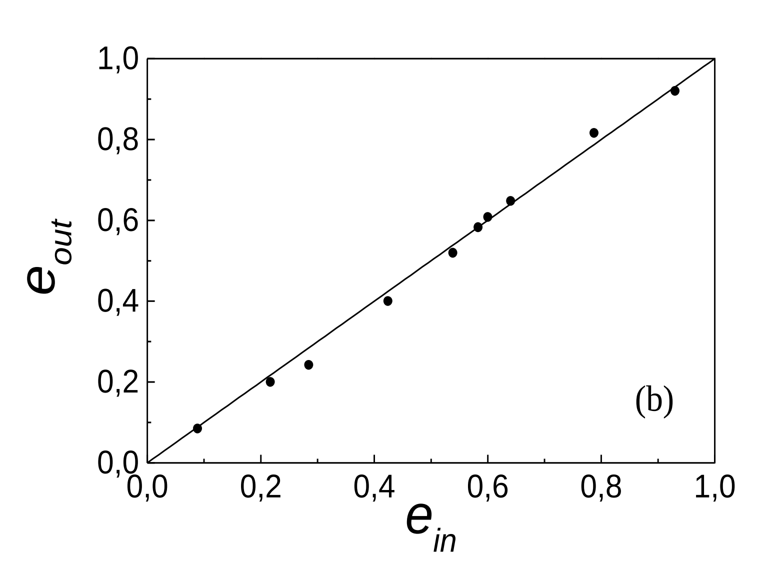
Фотоиндуцирани хирални структури

(при облъчване с **елиптично** поляризирана светлина)

2000



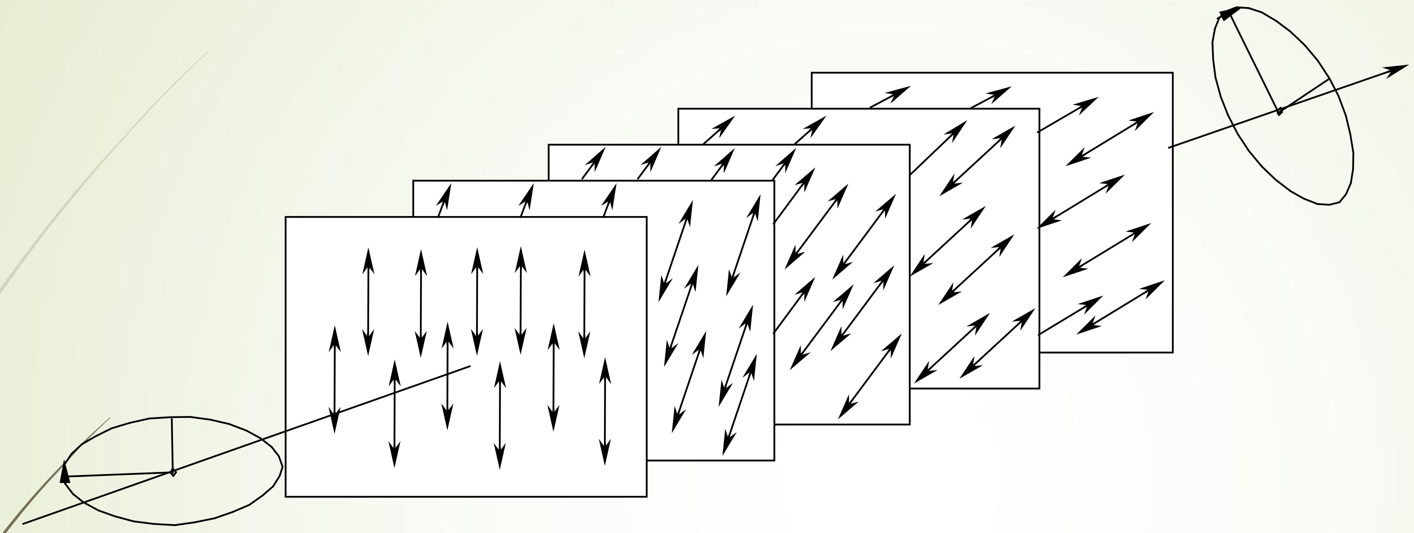




В това първо изследване, елиптичността и азимута бяха определяни с поляризатор и измерител на мощност...

L. Nikolova, L. Nedelchev, T. Todorov, Tz. Petrova, N. Tomova, V. Dragostinova, P.S. Ramanujam and S. Hvilsted "Self-induced light polarization rotation in azobenzene-containing polymers," *Appl. Phys. Lett* **77**, 657–659 (2000).

Механизъм за формирането им



$$\theta(d) = \frac{2e\delta}{1 - e^2} d$$

$\boldsymbol{\theta(d)}$ – ъгъл на завъртане

$\boldsymbol{e}$ – входна елиптичност

$\boldsymbol{\delta}$ – фазова разлика

APPLIED PHYSICS LETTERS VOLUME 77, NUMBER 5 31 JULY 2000

Self-induced light polarization rotation in azobenzene-containing polymers

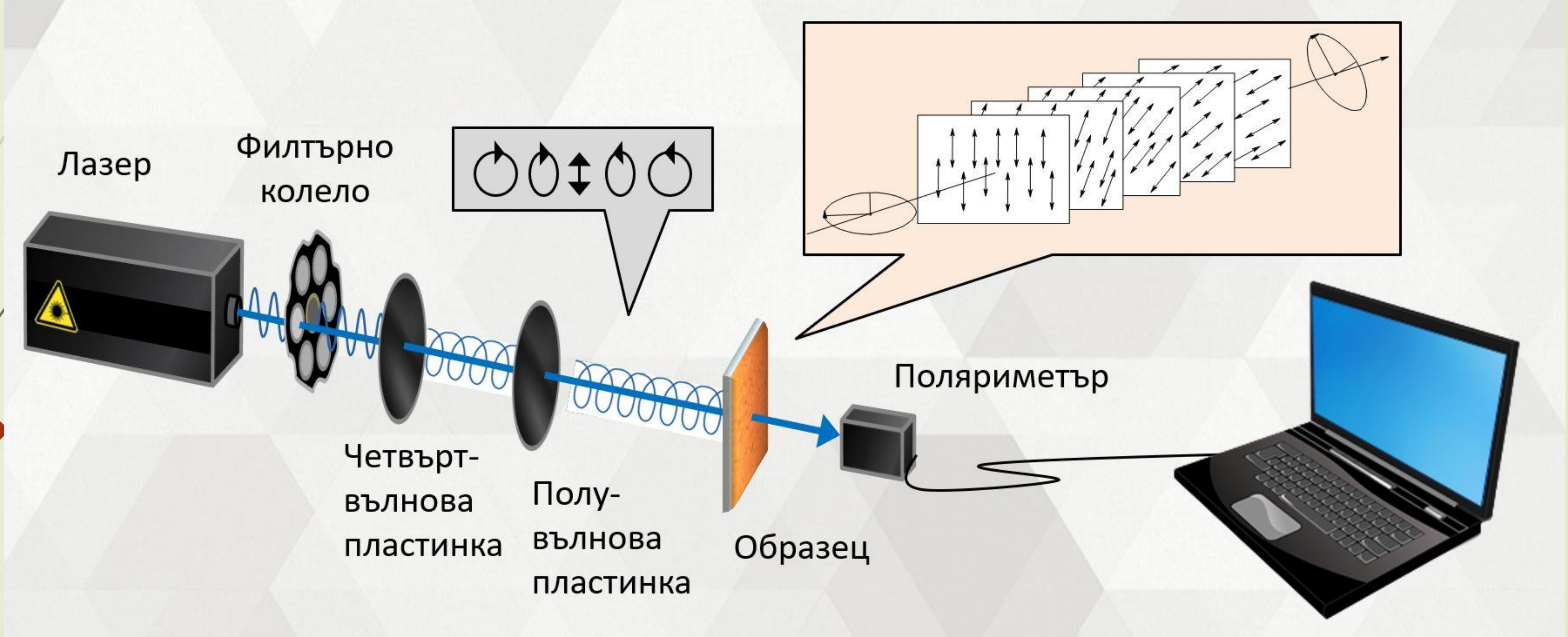
L. Nikolova,[a] L. Nedelchev, T. Todorov, Tz. Petrova, N. Tomova, and V. Dragostinova
Central Laboratory of Optical Storage and Processing of Information, Bulgarian Academy of Sciences, P.O. Box 95, 1113 Sofia, Bulgaria

P. S. Ramanujam and S. Hvilsted
Risoe National Laboratory, DK-4000 Roskilde, Denmark

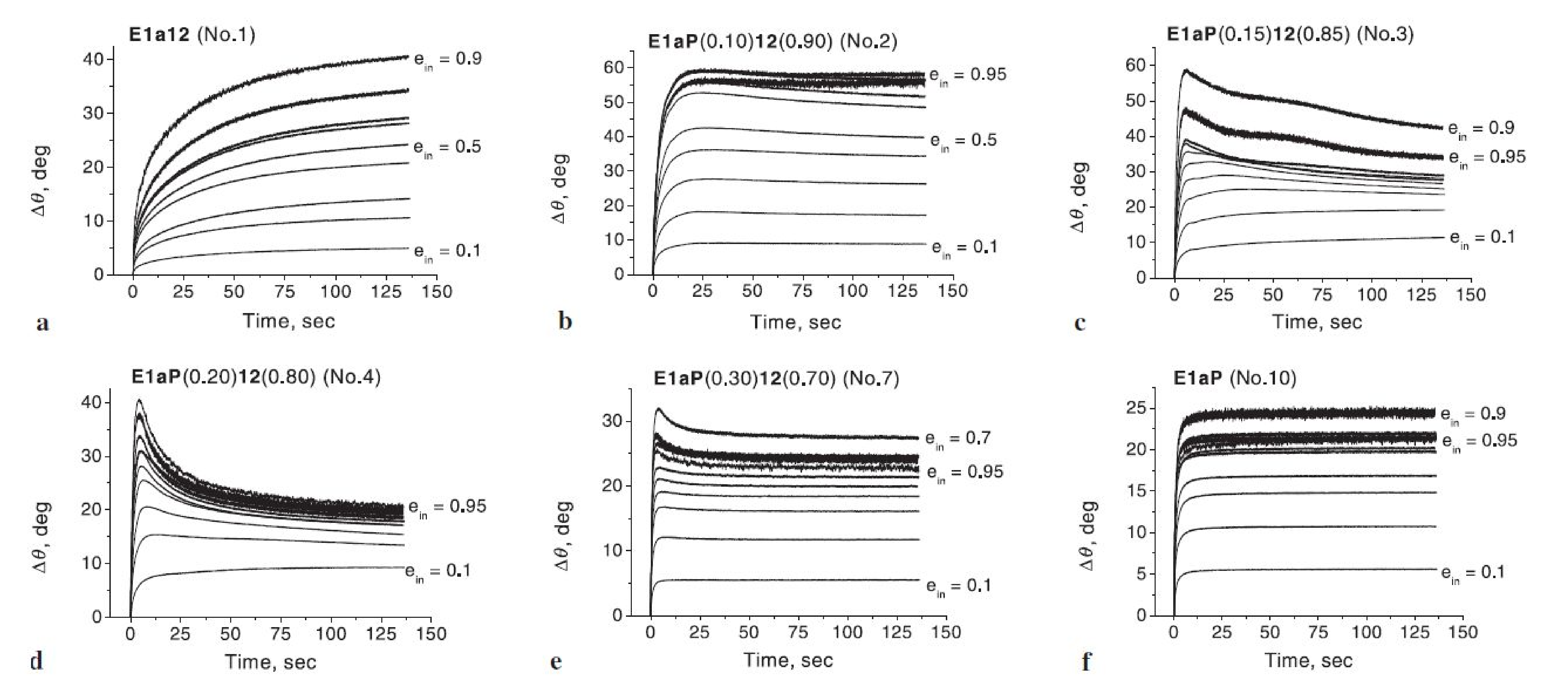
(Received 20 March 2000; accepted for publication 6 June 2000)

над 85 независими цитирания

Изследване на хиралните структури в реално време с поляриметър



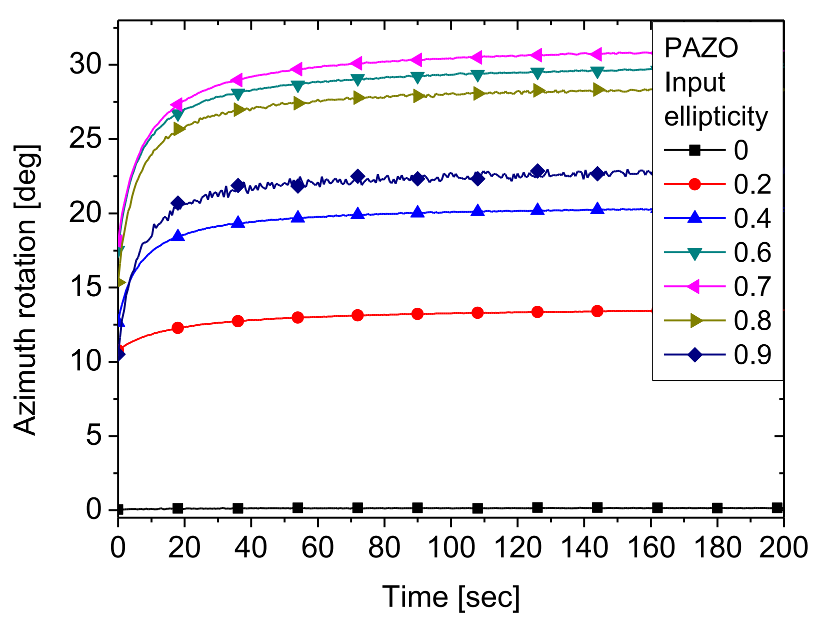
Кинетики на хирални структури



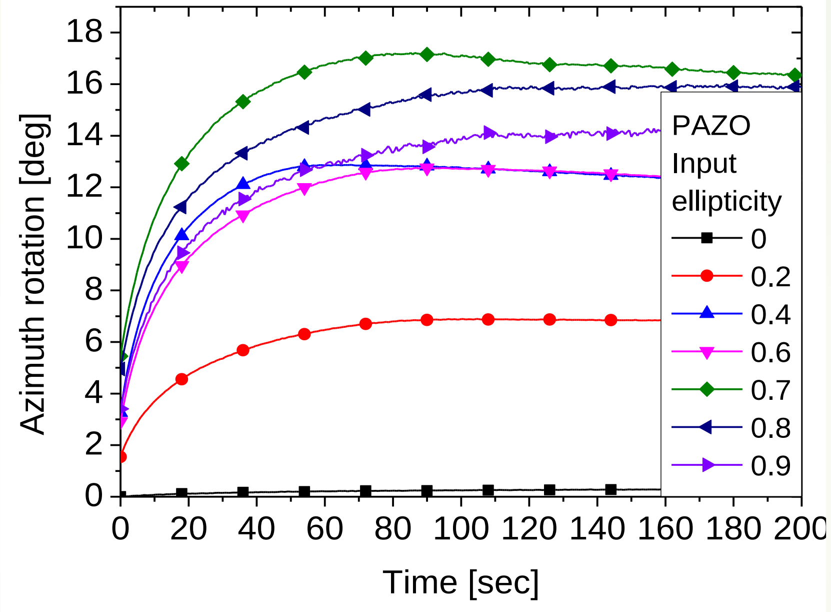
L. Nedelchev, L. Nikolova, A. Matharu and P.S. Ramanujam, "Photoinduced macroscopic chiral structures in a series of azobenzene copolyesters," *Appl. Phys. B* **75**, 671–676 (2002).

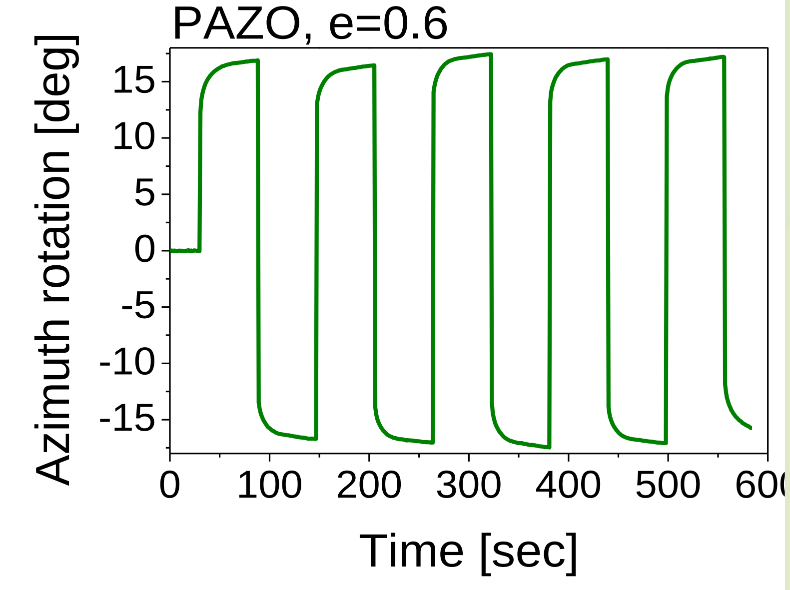
Кинетики на хирални структури

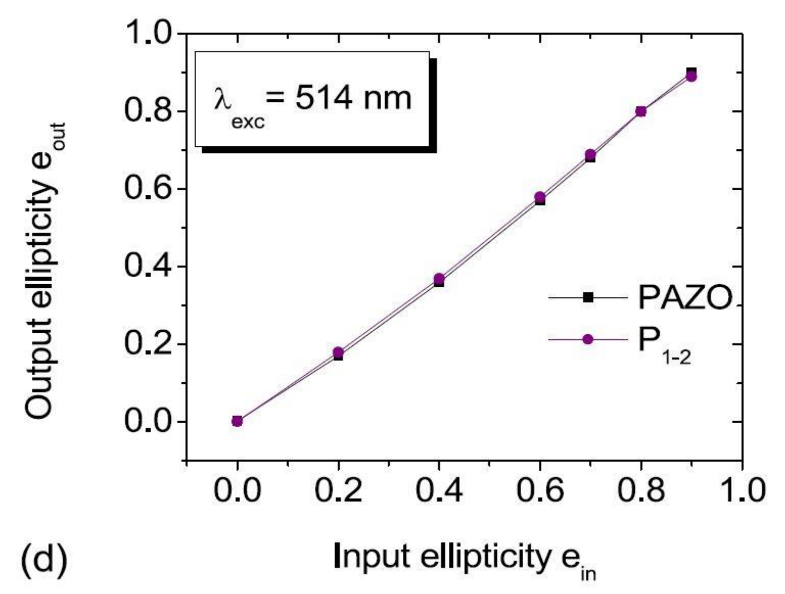
λ_{rec} = 444 nm



λ_{rec} = 514 nm







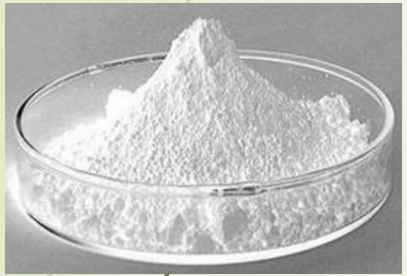
Изследвано е влиянието на дължината на вълната и интензитета на възбуждащото лъчение. Показана е обратимостта на посоката на хиралните структури при смяна на знака на входната елиптичност.

B. Blagoeva, L. Nedelchev, D. Nazarova, E. Stoykova, J. Park, J.. Reversible supramolecular chiral structures induced in azopolymers by elliptically polarized light: Influence of the irradiation wavelength and intensity. Applied Optics **61** (2022) B147-B155.

Азополимерни нанокомпозити

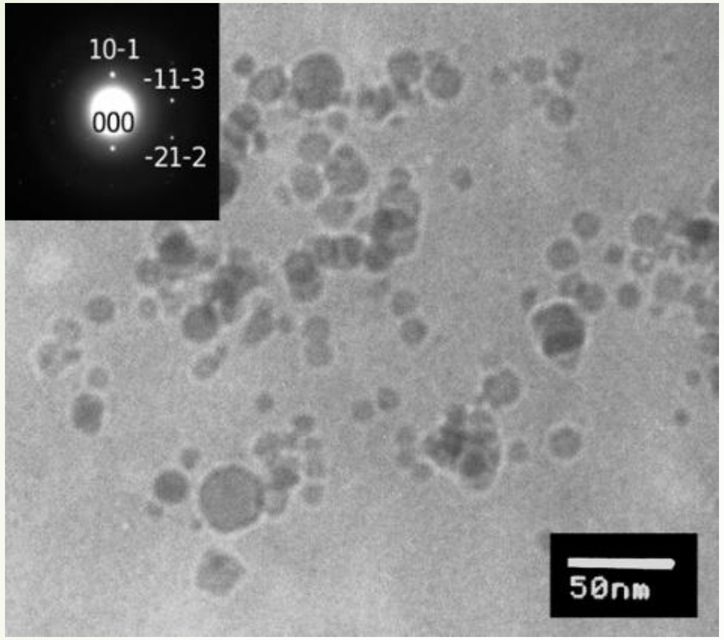
азополимер

+

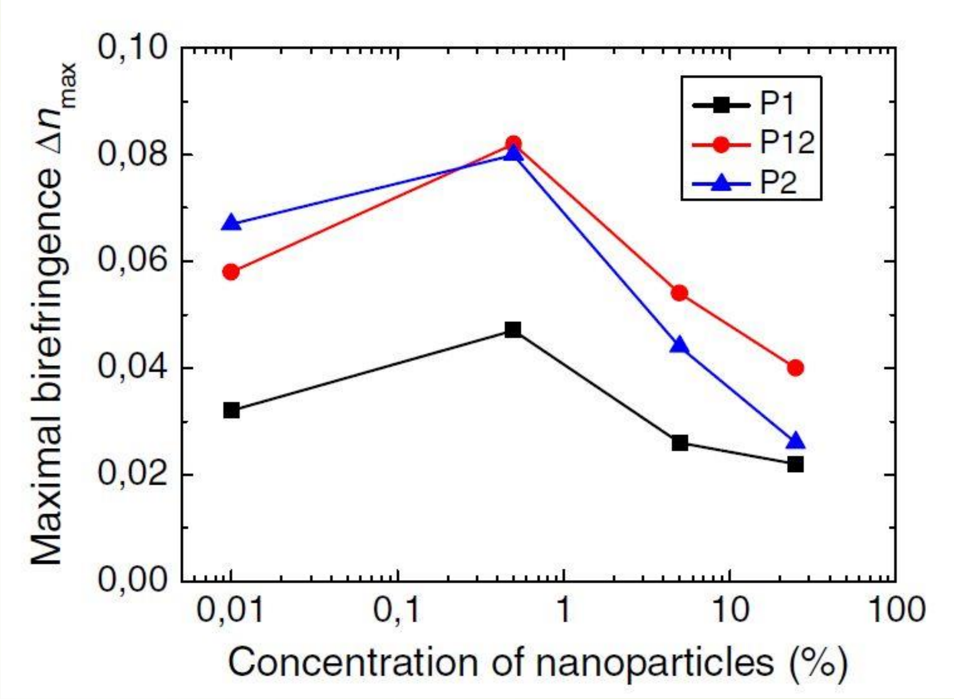


наночастици

=



Азополимер, дотиран с ZnO наночастици



2676 OPTICS LETTERS / Vol. 37, No. 13 / July 1, 2012

Increase of photoinduced birefringence in a new type of anisotropic nanocomposite: azopolymer doped with ZnO nanoparticles

Lian Nedelchev, Dimana Nazarova,* Violeta Dragostinova, and Daniela Karashanova

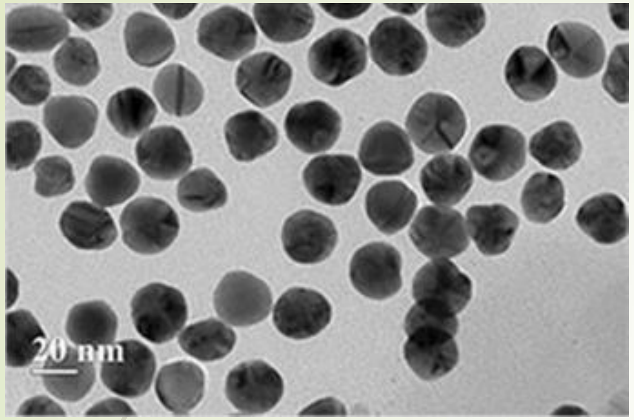
Institute of Optical Materials and Technology, Bulgarian Academy of Sciences, Acad. G. Bonchev Str. bl. 109, P.O Box 95, 1113 Sofia, Bulgaria

**Corresponding author: dimana@optics.bas.bg*

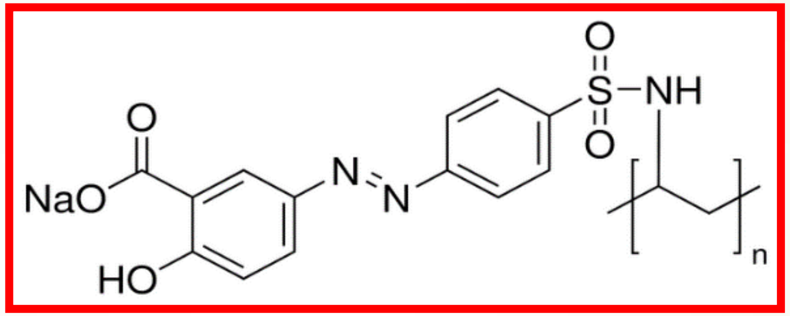
При P1, дотиран с 0,5% НЧ от ZnO, постигнахме 47% увеличение на Δn

По идея от статията:
N. Suzuki and Y. Tomita, Appl. Opt. **43**, 2125 (2004)
Фотополимер + НЧ SiO_2

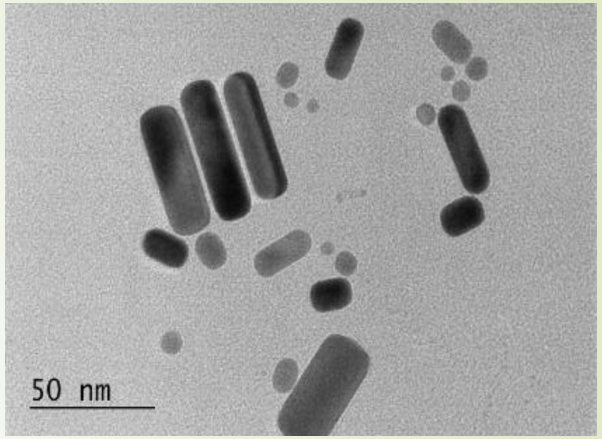
Състав на нанокомпозитните материали



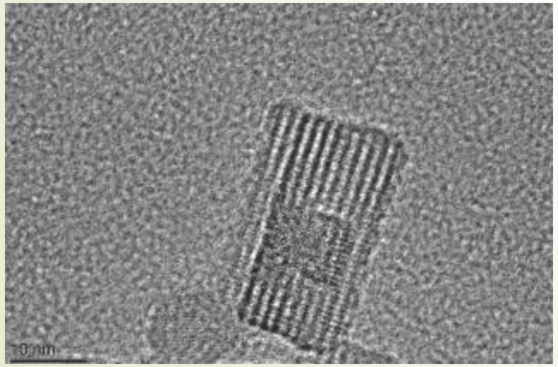
златни наносфери 20nm



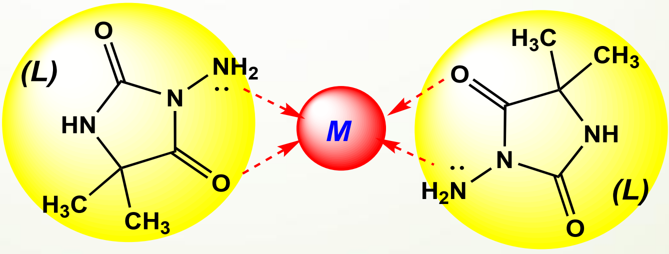
PAZO (Sigma Aldrich)



златни нанопръчици

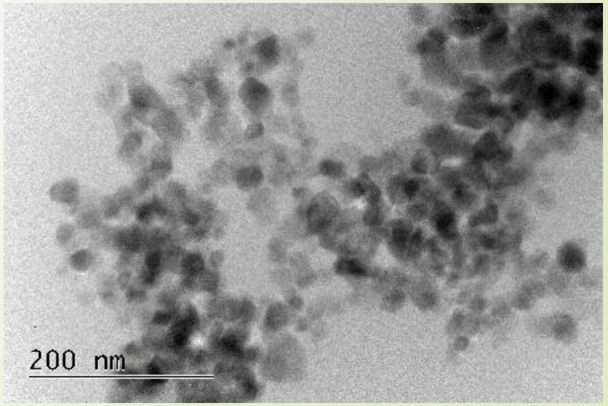


MFI (Mordenite Framework Inverted) зеолитни НЧ



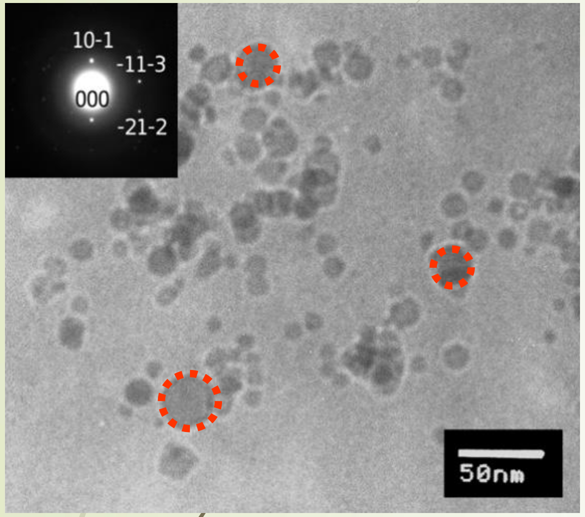
M = Cu^{2+} or Ni^{2+}

биологично активни метални комплекси

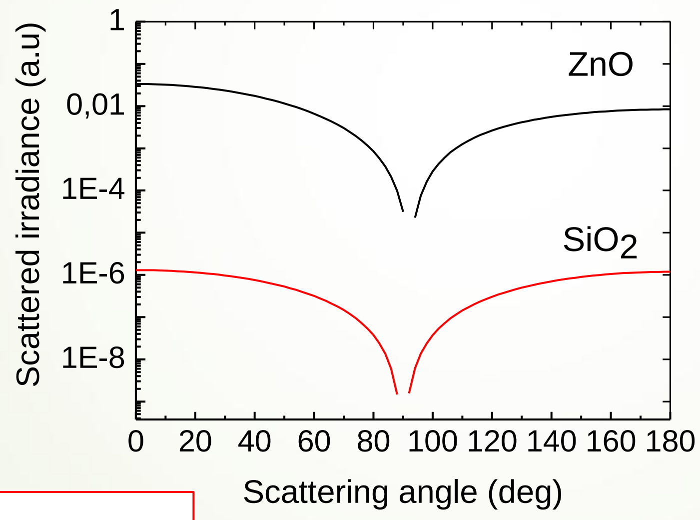


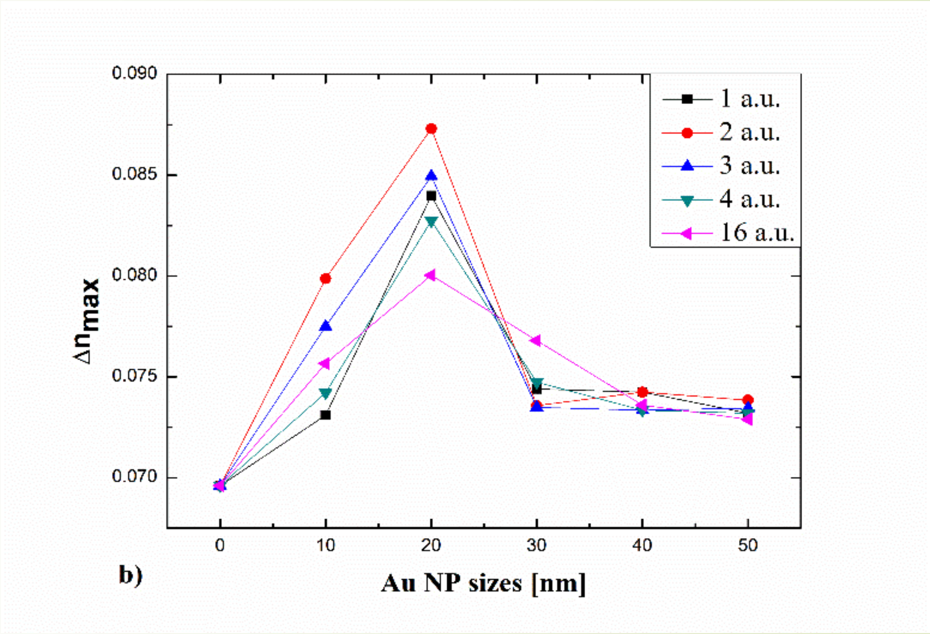
TiO_2 наночастици

Хипотези за механизма на повишаване на двулъчепречупването при нанокомпозити



1. Увеличение на свободния обем около азомолекулите, което подобрява мобилността им.





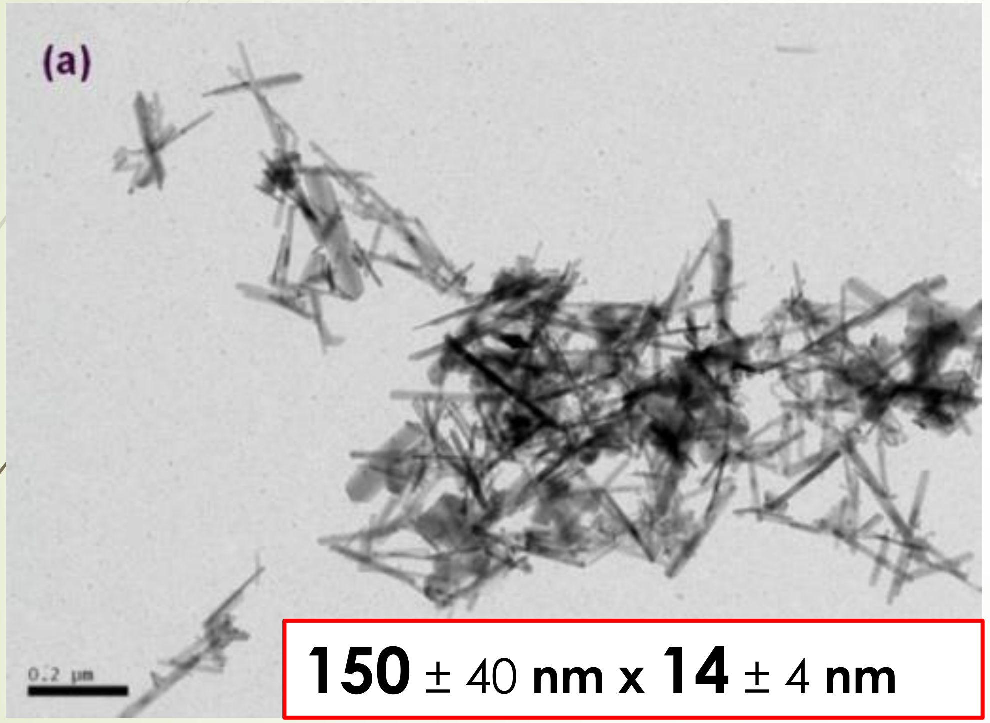
В този случай по-голямо влияние има ефекта на увеличение на свободния обем.

2. Увеличение на разсейването на светлината – така тя достига и до ориентираните перпендикулярно на слоя азомолекули.

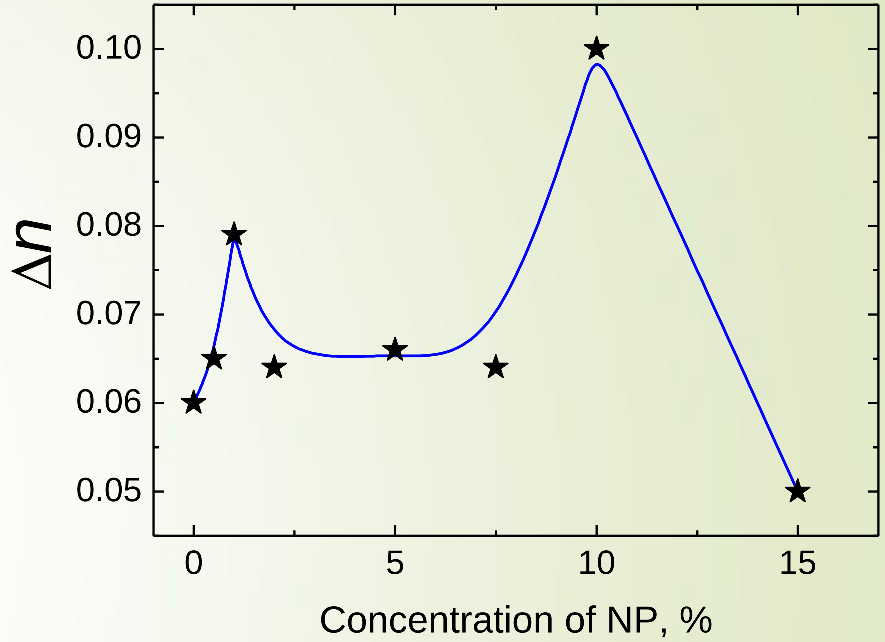
Berberova-Buhova, N., Nedelchev, L., Mateev, G., Stoykova, E., Strijkova, V., Nazarova, D. Influence of the size of Au nanoparticles on the photoinduced birefringence and diffraction efficiency of polarization holographic gratings in thin films of azopolymer nanocomposites. Optical Materials **121**, 111560 (9 pp), 2021.

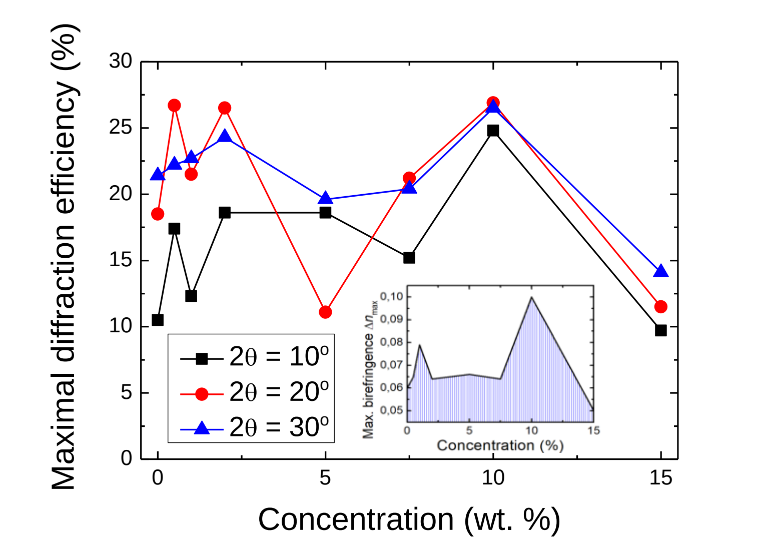
Азополимерни нанокомпозити

(PAZO дотиран с гьотитни нанопръчици)



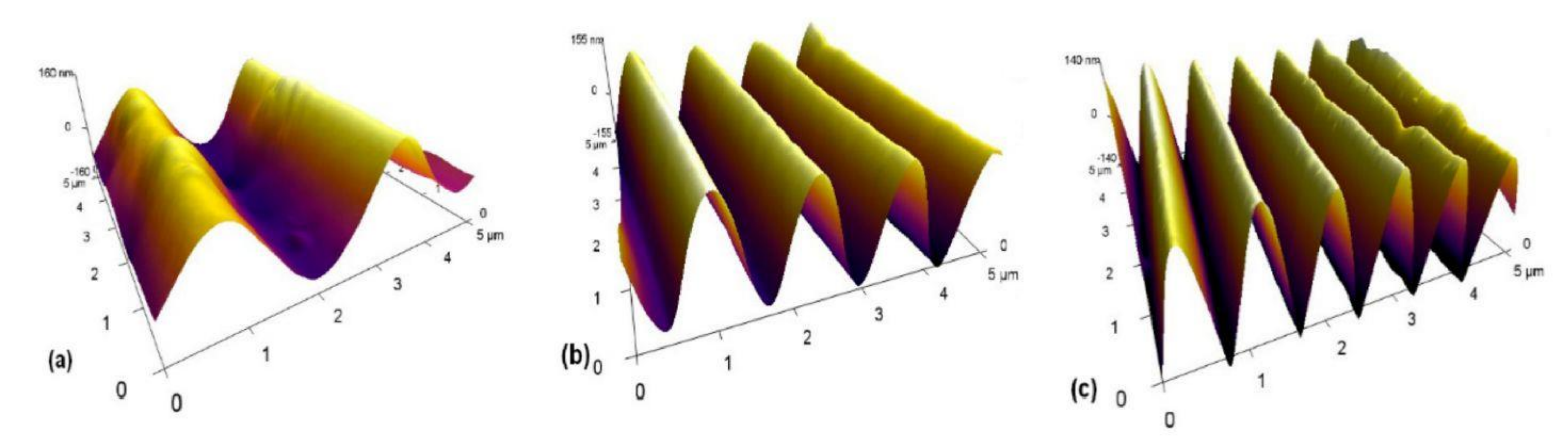
150 ± 40 **nm x 14** ± 4 **nm**





Nedelchev, L., **Mateev, G.**, **Strijkova, V.**, Salgueiriño, V., Schmool, D., **Berberova-Buhova, N.**, **Stoykova, E.**, **Nazarova, D.**. Tunable Polarization and Surface Relief Holographic Gratings in Azopolymer Nanocomposites with Incorporated Goethite (α-FeOOH) Nanorods. Photonics 8, 306 (12 pp) 2021.

Азополимерни нанокомпозити
(PAZO дотиран с гьотитни нанопръчици)



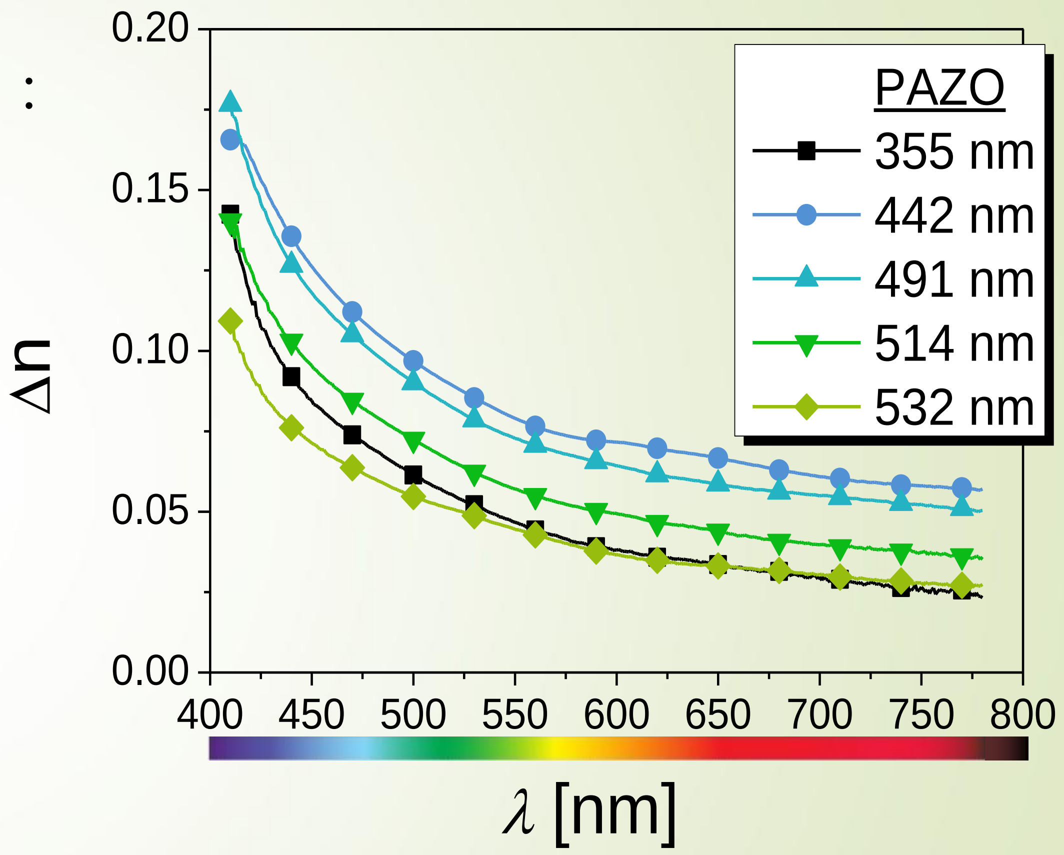
$\Lambda = 2.51\ \mu m$ at $2\theta = 10^\circ$ $\Lambda = 1.29\ \mu m$ at $2\theta = 20^\circ$ $\Lambda = 0.86\ \mu m$ at $2\theta = 30^\circ$

Спектрална зависимост на Δ*n*

Измерват се три спектъра на пропускане T(λ) :

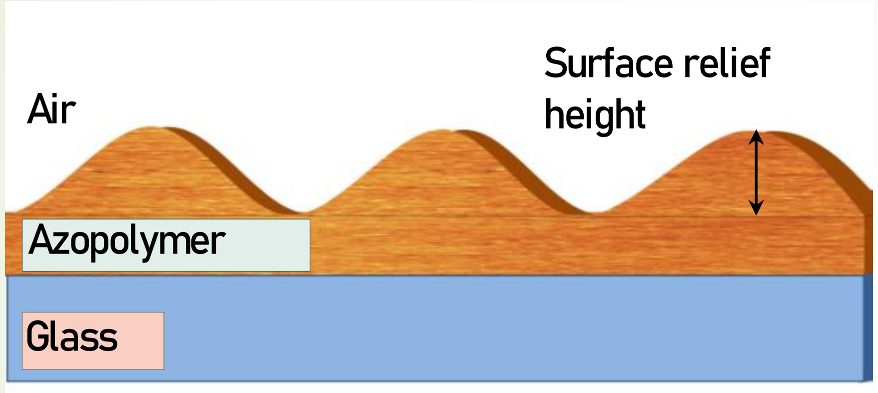
$T_{\|}^{non-exp}(\lambda)$, $T_{\perp}^{non-exp}(\lambda)$ и $T_{\perp}^{exp}(\lambda)$

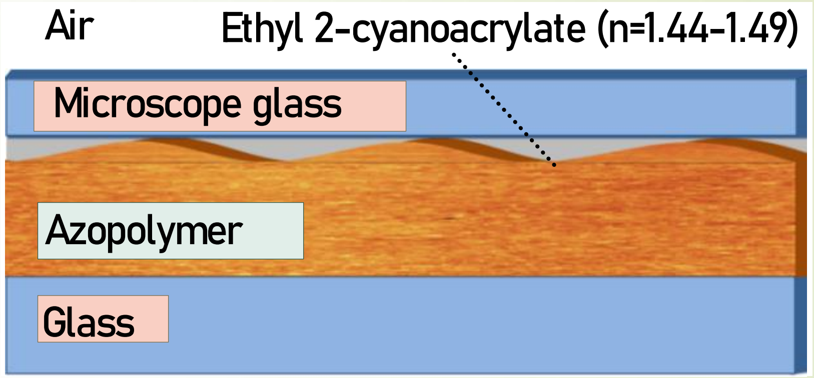
$$\Delta n(\lambda) = \frac{\lambda}{\pi d} \, arcsin\sqrt{\frac{T_{\perp}^{exp} - T_{\perp}^{non-exp}}{T_{\|}^{non-exp}}}$$

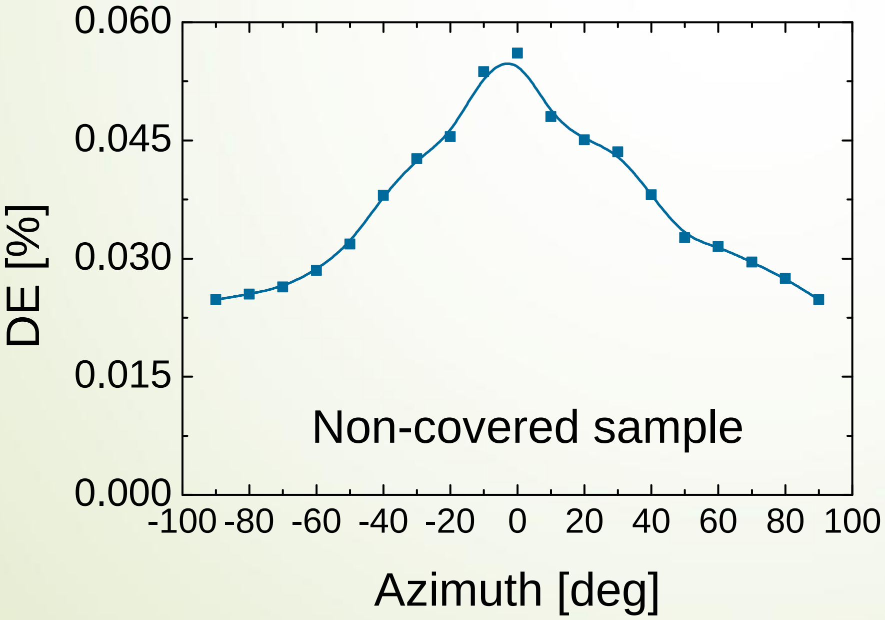


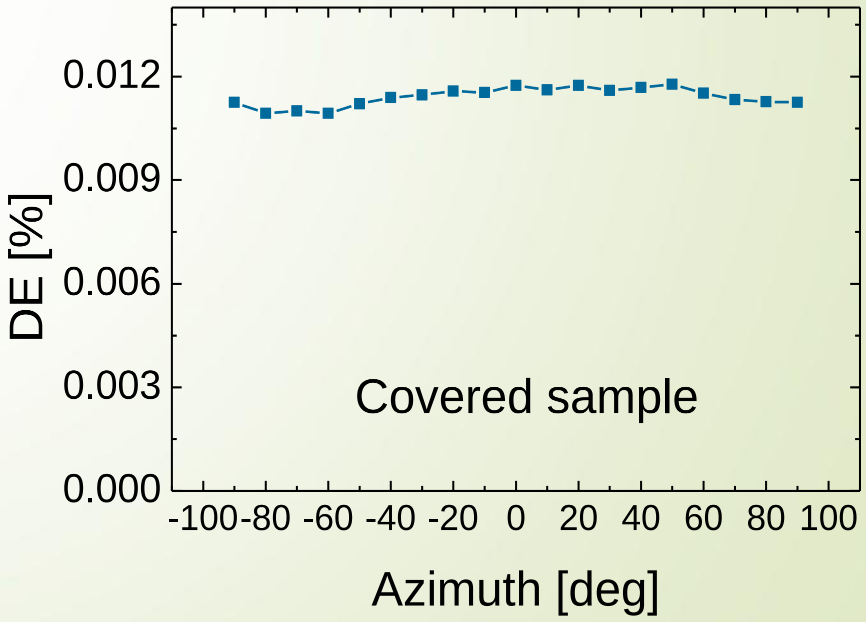
L. Nedelchev, D. Ivanov, B. Blagoeva, D. Nazarova, "Optical anisotropy induced at five different wavelengths in azopolymer thin films: Kinetics and spectral dependence". J. Photochem. Photobiol. A 376 (2019) 1-6.

Подобряване свойствата на кръгово-поляризационен светоделител









Подобряване свойствата на кръгово-поляризационен светоделител

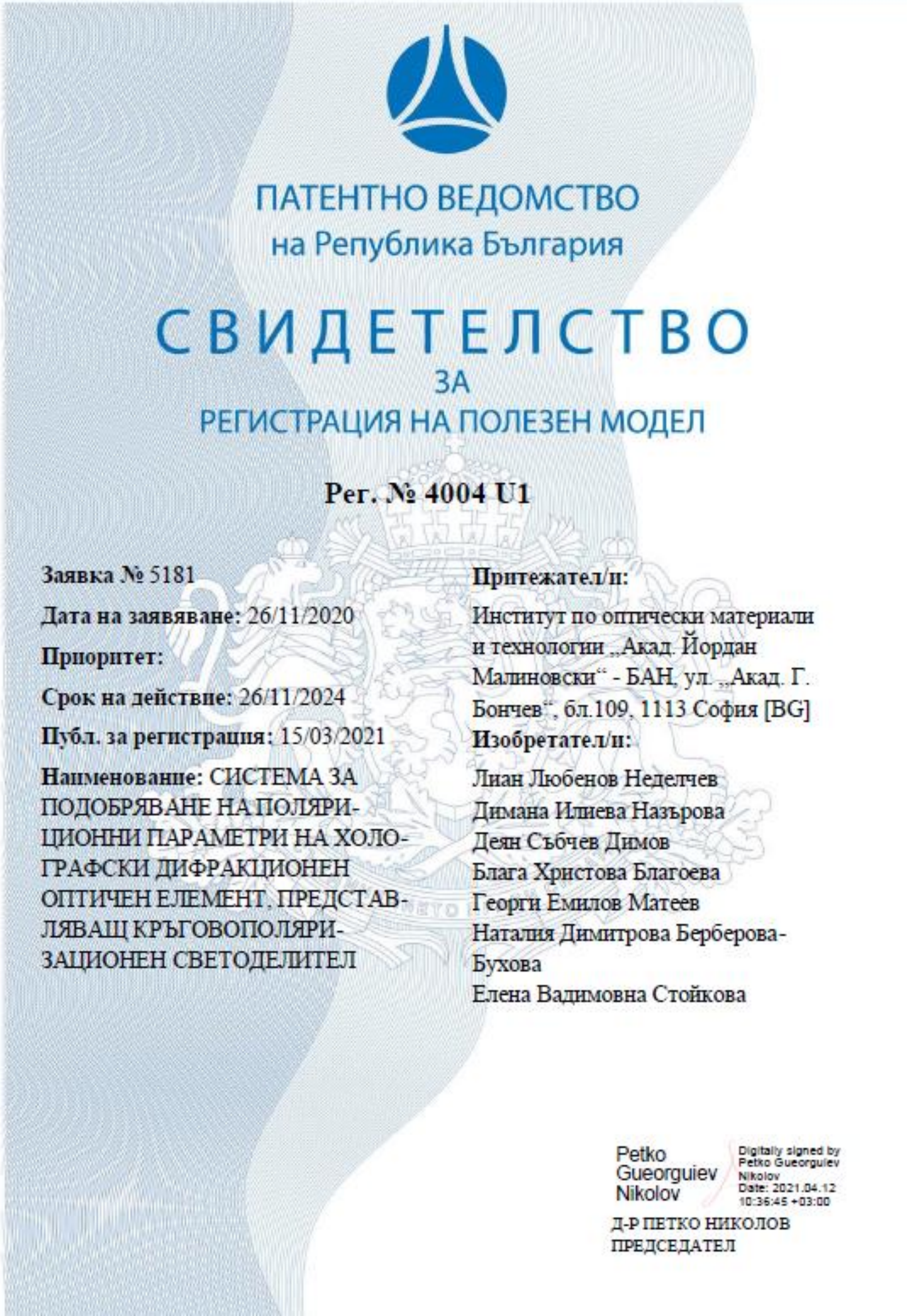
ПОЛЕЗЕН МОДЕЛ Рег. № **4004 U1**

СИСТЕМА ЗА ПОДОБРЯВАНЕ НА ПОЛЯРИЗАЦИОННИ ПАРАМЕТРИ НА ХОЛОГРАФСКИ ДИФРАКЦИОНЕН ОПТИЧЕН ЕЛЕМЕНТ, ПРЕДСТАВЛЯВАЩ КРЪГОВОПОЛЯРИЗАЦИОНЕН СВЕТОДЕЛИТЕЛ

Заявка № 5181;
Дата на заявяване: 26/11/2020;
Срок на действие: 26/11/2024;
Публ. за регистрация: **15/03/2021**

Изобретател/и: Лиан Любенов Неделчев, Димана Илиева Назърова, Деян Събчев Димов, Блага Христова Благоева, Георги Емилов Матеев, Наталия Димитрова Берберова-Бухова, Елена Вадимовна Стойкова

Притежател/и: Институт по оптически материали и технологии „Акад. Йордан Малиновски“ - БАН, ул. „Акад. Г. Бончев“, бл.109, 1113 София



ПАТЕНТНО ВЕДОМСТВО
на Република България

СВИДЕТЕЛСТВО
ЗА
РЕГИСТРАЦИЯ НА ПОЛЕЗЕН МОДЕЛ

Рег. № 4004 U1

Заявка № 5181
Дата на заявяване: 26/11/2020
Приоритет:
Срок на действие: 26/11/2024
Публ. за регистрация: 15/03/2021
Наименование: СИСТЕМА ЗА ПОДОБРЯВАНЕ НА ПОЛЯРИЗАЦИОННИ ПАРАМЕТРИ НА ХОЛОГРАФСКИ ДИФРАКЦИОНЕН ОПТИЧЕН ЕЛЕМЕНТ, ПРЕДСТАВЛЯВАЩ КРЪГОВОПОЛЯРИЗАЦИОНЕН СВЕТОДЕЛИТЕЛ

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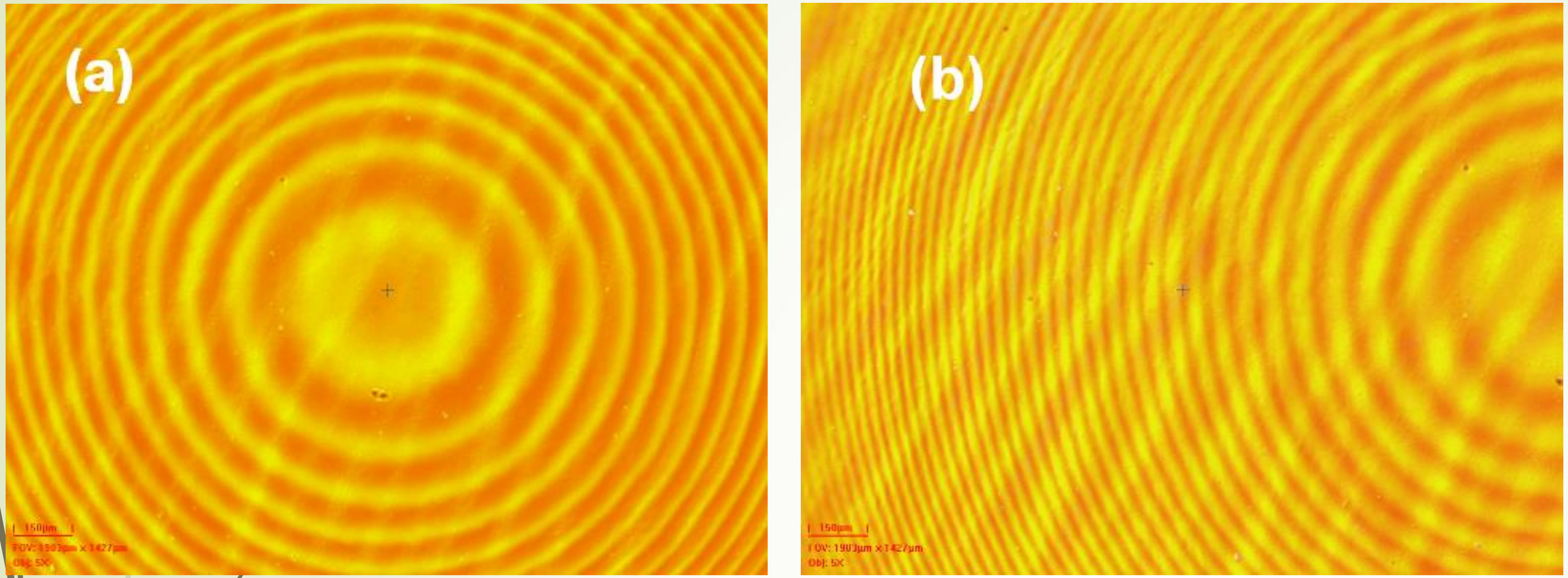
Институт по оптически материали и технологии „Акад. Йордан Малиновски“ - БАН, ул. „Акад. Г. Бончев“, бл.109, 1113 София [BG]

Изобретател/и:
Лиан Любенов Неделчев
Димана Илиева Назърова
Деян Събчев Димов
Блага Христова Благоева
Георги Емилов Матеев
Наталия Димитрова Берберова-Бухова
Елена Вадимовна Стойкова

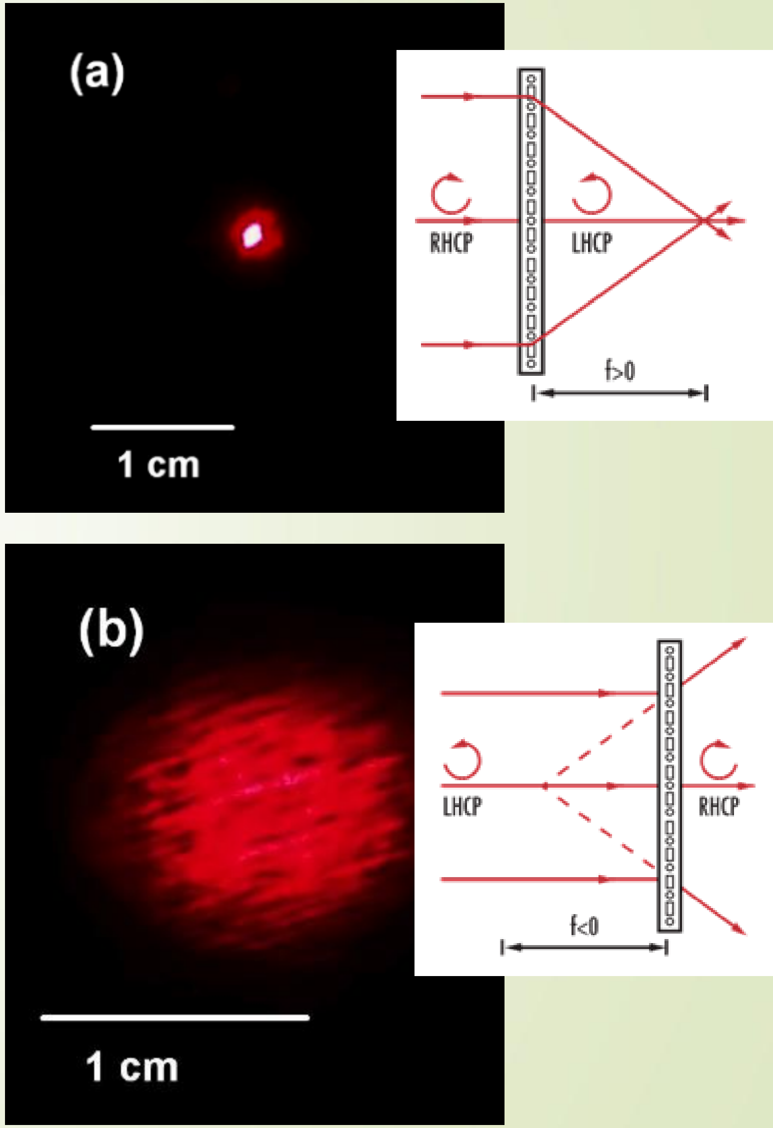
Petko Gueorguiev Nikolov
Digitally signed by Petko Gueorguiev Nikolov
Date: 2021.04.12 10:36:45 +03:00

Д-Р ПЕТКО НИКОЛОВ
ПРЕДСЕДАТЕЛ

Поляризационно-селективна холографска леща



Изображения на централната част на лещата чрез поляризационен микроскоп

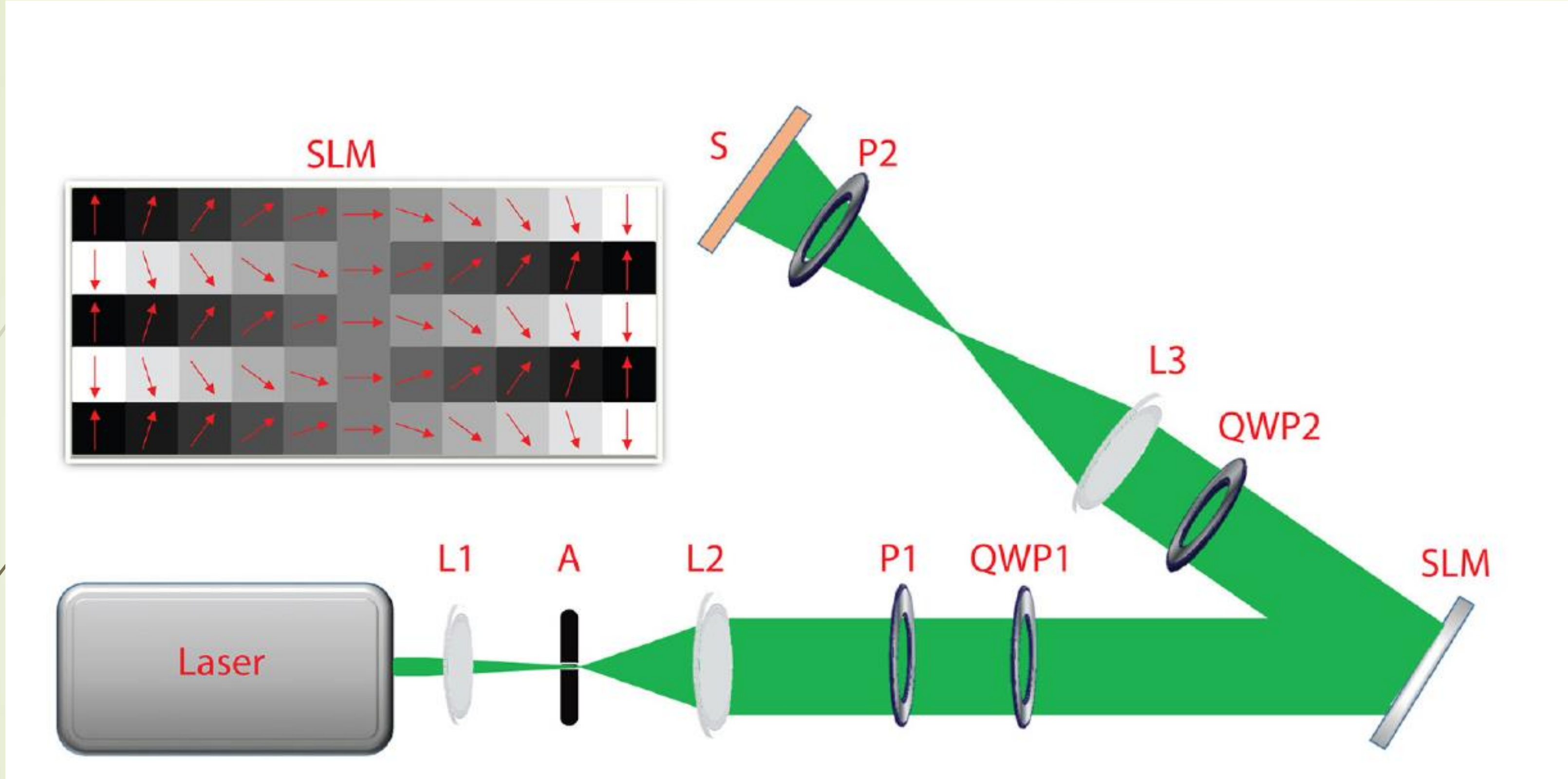


За RCP светлина лещата е събирателна (a), а за LCP е разсейвателна (b).

Nedelchev, L, Mateev, G, Nikolova, L, Nazarova, D, Ivanov, B, Strijkova, V, Stoykova, E, Choi, K, Park, J. In-line and off-axis polarization-selective holographic lenses recorded in azopolymer thin films via polarization holography and polarization multiplexing. *Applied Optics* (приета за печат), 2022.

Перспективи за бъдещи изследвания

Цифрова поляризационна холография

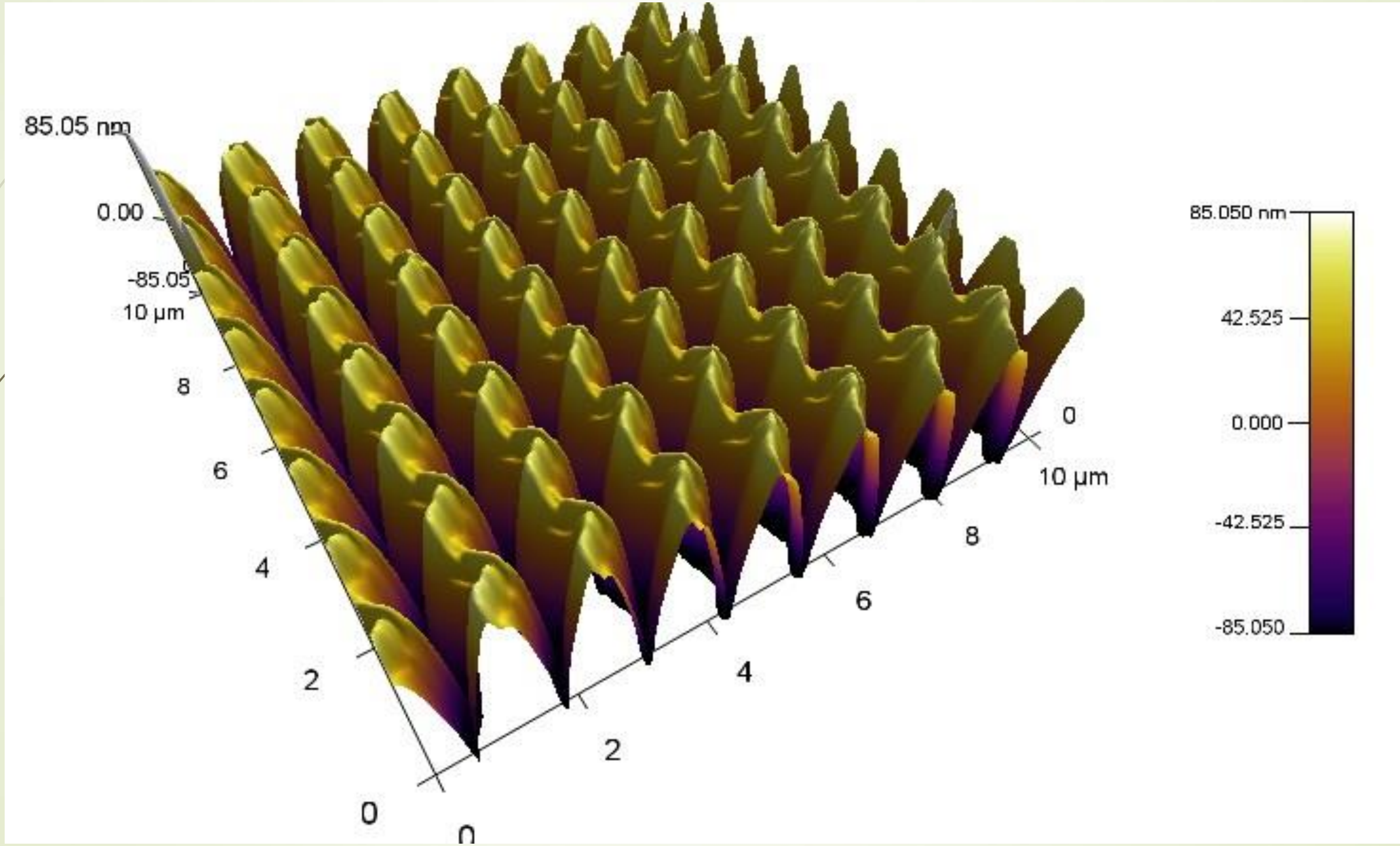


No. 16 | 8 Aug 2016 | OPTICS EXPRESS 18297

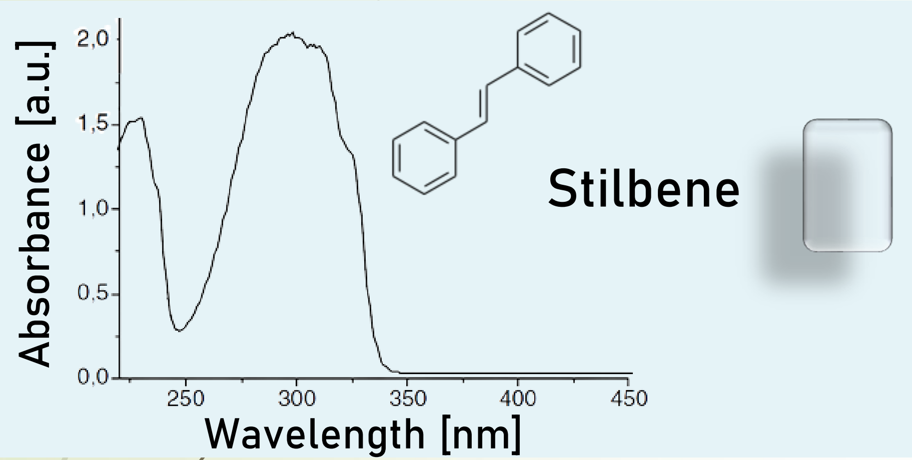
Digital polarization holography advancing geometrical phase optics

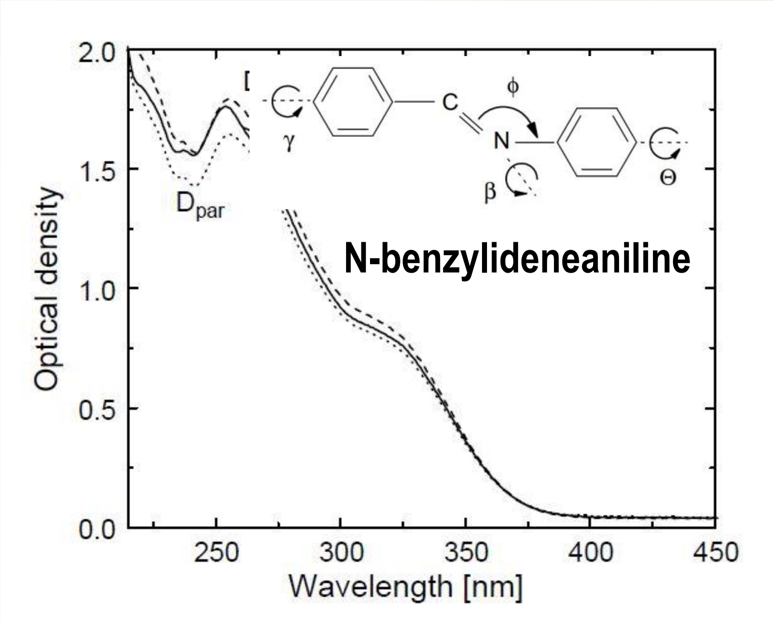
LUCIANO DE SIO,[1,*] DAVID E. ROBERTS,[1] ZHI LIAO,[1] SARIK NERSISYAN,[1] OLENA USKOVA,[1] LLOYD WICKBOLDT,[1] NELSON TABIRYAN,[1] DIANE M. STEEVES,[2] AND BRIAN R. KIMBALL[2]

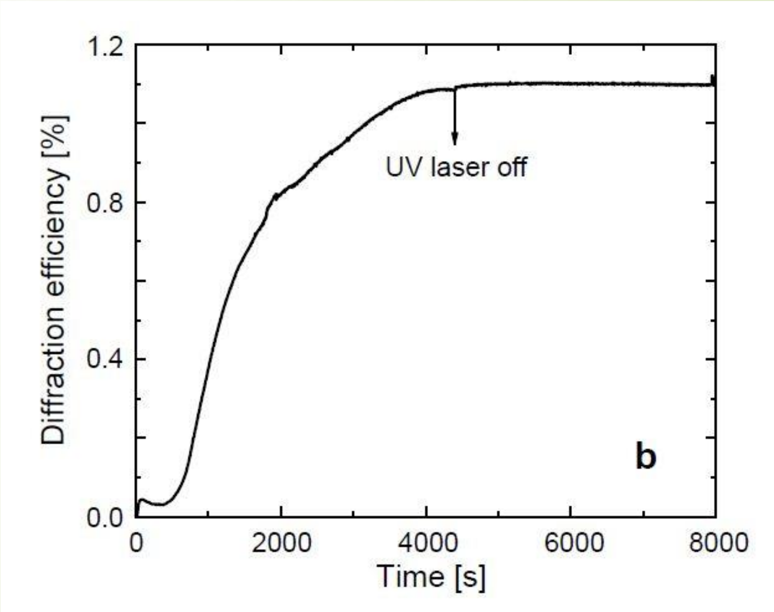
Повърхностен релеф с по-сложна форма



Анизотропни материали, прозрачни във видимата област







Предизвикателства: записът в тези среди изисква мощен и кохерентен лазер в УВ областта; все още ниска ефективност

D. Ilieva, L. Nedelchev, Photoinduced anisotropy and polarization holography on UV exposure in films of N-benzylideneaniline in PMMA matrix. Optica Applicata, 42, (2012) 207-214.

Благодарности

- на моите родители, учители и научни ръководители;

- за финансирането, получено по национални и международни проекти;

- на **всички** колеги от ИОМТ за подкрепата и съвместната работа!

Благодаря за вниманието!