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Fundamentals of holographic data storage: Diffraction of light by volume holographic gratings LECTURE 2: "Optical Media and Holographic Techniques"

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Fundamentals of holographic data storage: Diffraction of light by volume holographic gratings

LECTURE 2

"Optical Media and Holographic Techniques"

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CONTENTS

II.1.- Objectives

- We shall present a general scope of the current status of the most promising photo-materials, that can be synthesized. The aim is to develop holographic volume gratings to be applied to data storage.

- For this task we need to study first general features and physical parameters defining the various photo-materials under consideration.

- We shall present the most relevant holographic techniques and applications

- We shall end by presenting non conventional effects and the possible future applications.

II.2.- Some antecedents and an overview

We live in a society with a high demand for improvements in information technologies.

Conventional technologies: magnetic, optical, magneto-optical disks, semi-conductor memorie have been able to face this demand.

Optic disks based upon holographic techniques can store data which amount to improvements a factor 200 with respect to magnetic disks (i.e. 200 Gb).

The basic technique for such storage was proposed in 1963 by *Pieter van Heerden* (Polaroid, Cambridge, Massachusetts, USA). The binarized data are implemented in a holographic mater forming 2-D pages of information: holographic data storage (HDS).

Since that date enormous efforts have been made in order to achieve the most optimized procedure: i.e. materials research, holographic fidelity, low scattering leading to quite a diversi field.

Research in photorefractive crystals started in the 1960's. In 1966, *Ashkin* discovered the photorefractive effect in $LiNbO_3$ (and $LiTaO_3$). In 1968 in Bell Laboratories *Chen et al.* suggest the application for data storage. The initial problem was that erase was generated while readin the stored data. The great advantage was real time storing, retrieval, erasing and rewriting. In 1998 *Karsten Buse's* team developed a doped $LiNbO_3$ with manganese, and reading with low energy was achieved.

Photopolymers have been the subject of many researches (i.e., Hughes Aircraft, Polaroid, DuPont, Lucent and then InPhase, Vavilov Institute of Saint Petersburg, Univ of Alicante). Problems have arisen due to dimensional stability and scattering which have prevented the achievement of permanent recording.

Hybrid organic-inorganic materials like photopolymer glasses (*Cheben* and *Calvo*, 2001), and s gel techniques (*Ebelmen*, 1884), present high performances for improving dimensional stability and high refractive index modulation.

Since the 1990's various laboratories and research centers are seriously working on desktop HDS: i.e., IBM, InPhase, Aprilis, CalTech (Pasadena, *Demitri Psaltis*) with various promising results. The 21st century is poised for the commercial acceptance of holographic data storage.

II. 3.- MAIN PHYSICAL REQUIREMENTS FOR PERFORMING A HOLOGRAPHIC MEMORY

•**Volume storage requirements**:
Photomaterials allow FOR sensitization with programmable thickness (> 1mm.)

•**Total number of independent storage cells (***P. van Veerden*, 1963**):**

$$N_0 = \left(\frac{d}{\lambda_0}\right) \Big/ \left(\frac{\lambda_0}{a}\right)^2 = V/\lambda_0^3 : \underbrace{\textbf{number of separated resolved } \lambda_0 \textbf{ / solid angle}}$$

•Storage capacity: $C \cong N_0 \, \boldsymbol{log}_2 \left(Signal/Noise \right)$

•Minimum volume to store 1 bit: $\approx \lambda^3$

•Order of magnitude of the storage density (λ = 400 nm): 10 Tbits/cm3

•1 sheet of codified data: 1024X1024 = 1 Mpixels

•High refractive index modulation: $\Delta n >> 10^{-2}$

•**Mechanical features**:

•Accessible high polished surface (optical quality)

•Rigidity: Glass hardness as a reference (i.e. **microhardness testing**)

•Resistance to mechanical polishing

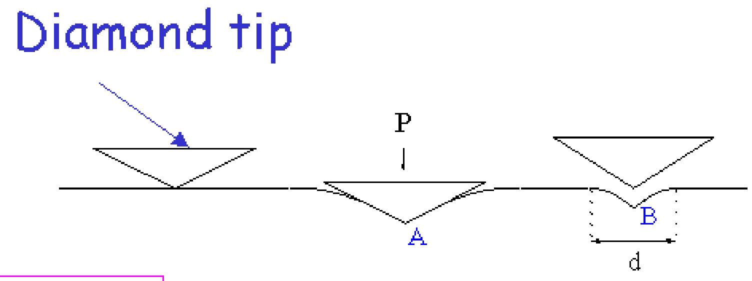
•**Thermal requirements:**

•Thermal stability before and after the recording (0º-60º C)

•Dimensional stability

Microhardness of materials

Microhardness



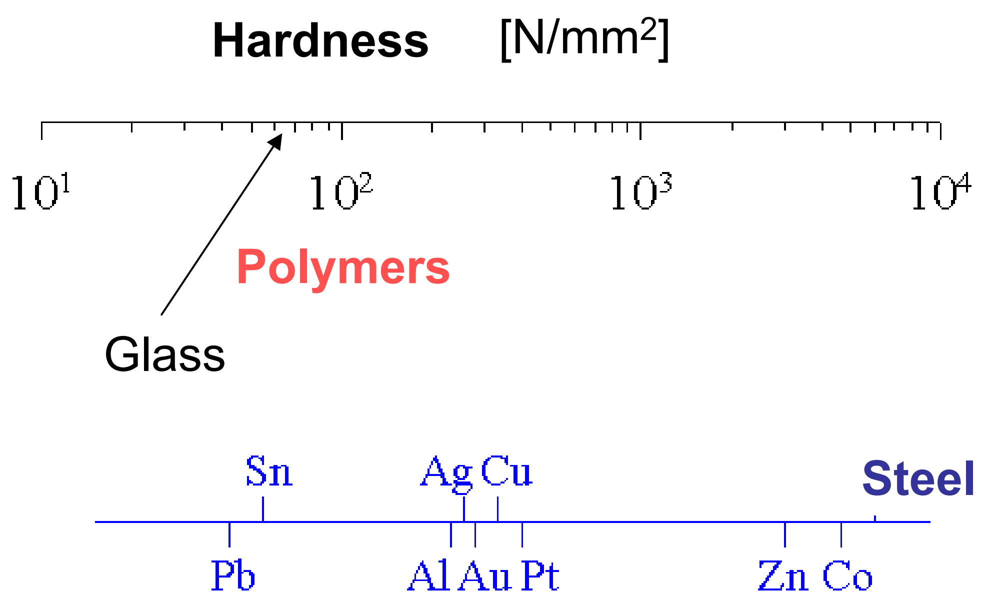
- Elastic Recovery (A→B)
- Permanent Deformation (H)
- Creep: $H \propto t^{-k}$
- Viscoelastic Relaxation

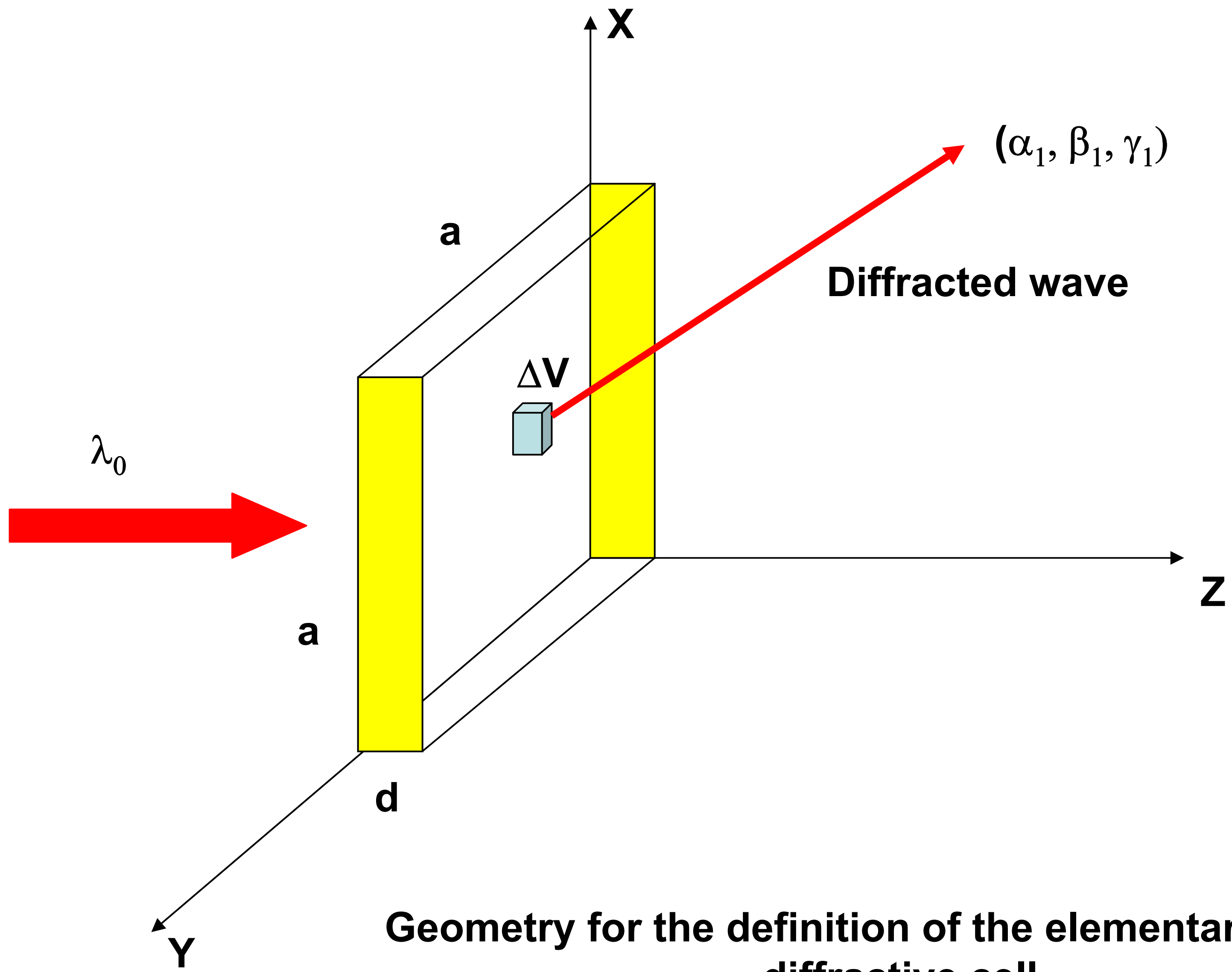
$$H = \frac{P}{A} = \alpha \frac{P}{d^2}$$

P: Load
A: Area
α: geometric factor

After: F.J. Baltá Calleja, D.S. Sanditov, V.P. Privalko, “Review: the microhardness of non-crystalline materials” , J. Mater. Sci., 37, 4507-4516 (2002). Also: J. Robredo, M.L. Calvo, M. Dusollier, Verres et Réfractaires, **24**(2), 49(1970).

Microhardness of Materials





Geometry for the definition of the elementary volume diffractive cell

II.4.- COMPONENTS OF A HOLOGRAPHIC MEMORY

- **II.4.1.- Luminous source**
- **II.4.2.- Spatial light modulators (SLM)**
- **II.4.3.- Detectors**
- **II.4.4.- Other components**

II.4.1.- THE LUMINOUS SOURCE

Basic requirements:

High temporal coherence: Laser sources

Coherence time:

$$\tau_c = \frac{l_c}{c} = \frac{1}{\Delta\nu}; \ \ \Delta\nu: \text{ spectral bandwidth}$$

$$\text{Example: } l_c = 1\text{Km}; \ \ \tau_c = 3\times 10^{-6} s; \ \ \Delta\nu = 0.3 MHz$$

Wavelength stability:

In a reasonable high temporal interval operation.

IMPORTANT: In thick volume holographic gratings: We want high spectral sensitivity, i.e., the entire visible spectrum (488-690 nm) and near IR (up to 830 nm)

Unstable sources can cause reduction of the diffraction efficiency.

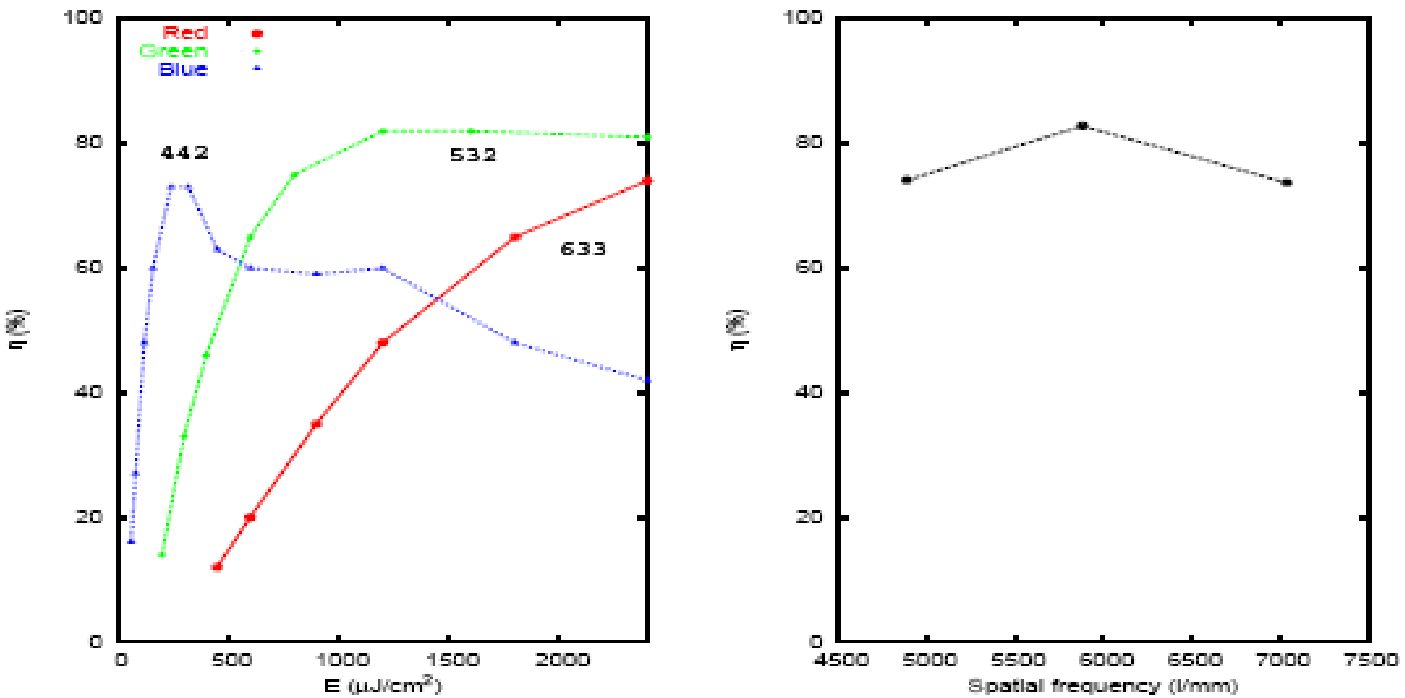
C*ross-talk* could appear for multiplexed holographic gratings.

Input power: It is in order of magnitude, about 100mW.

High photon flux ⇒ Low writing time ⇒ Data flux accelaration

Types of laser sources: Solid state: (i.e., Nd:YAG (532 nm,), semiconductor lasers: GaN family of materials (420 nm), InGaAIP (630-690 nm), α-DFB (*Angle-Grating Distributed Feedback*) (400 mW, 690 nm. and high coherence) are required for mode stabilization

EXAMPLE OF THE DEPENDENCE OF THE DIFFRACTION EFFICIENCY ON EXPOSURE ENERGY FOR RECORDING WAVELENGHTS



(a) Dependence of the diffraction efficiency of BBVPan plates on exposure energy for each of the recording wavelengths. (b) Maximum diffraction efficiency values for each of the recording spatial frequencies.

After M. Ulibarrena et al., 15 December 2003 / Vol. 11, No. 25 / OPTICS EXPRESS 3386

II.4.2.- SPATIAL LIGHT MODULATORS (SLM)

- **Object beam modulation:**

A required operation for the codified storage in 2-D (1 page)

- **Types of SLM:**
- **Liquid crystals (*Twisted nematic*):**
- **Parameters:**

  Frame rate: 30 ms.
  Spatial resolution: 1.024X1.024 pixels. Pixel size: 6μm-20μm
- **Ferroelectric crystals:** 100μs, similar spatial resolution.
- **Deformable Mirror Devices *(DMD*):** 2KHz, 850X600 pixels, High contrast: 800:1
- In general, the SLM operates by sampling the optical signal. According to the Whittaker-Shannon sampling theorem, the associated transmission function is a finite sum:

$$t(x,y)=\sum_{m=1}^{N}\sum_{n=1}^{N}a_{mn}rect\left(\frac{x}{p}-m\right)rect\left(\frac{y}{p}-n\right)$$

$$a_{mn}=\{1,0\};\ \text{binarized signal}$$

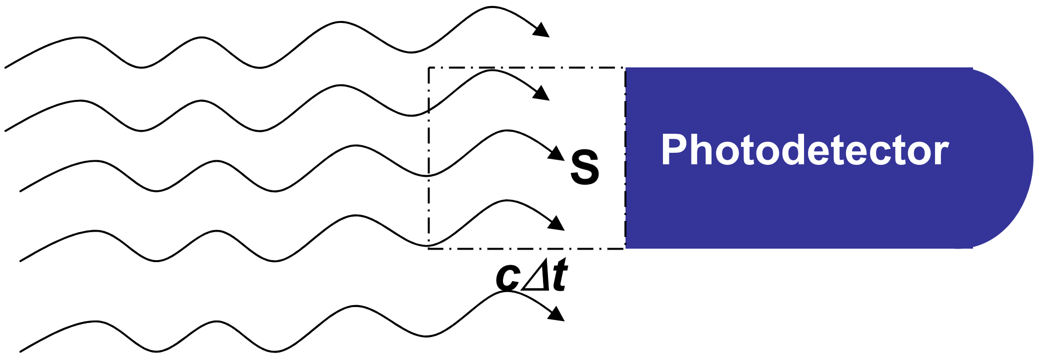
II.4.3.- DETECTORS

- **Charge Coupled Devices (CCD)**
- Spatial resolution: 1024X1024 pixels
- Quantum efficiency: 70%-20%
- According to the detection probability:

$$P(\bar{r},t)\Delta t = \alpha(\lambda) c S \Delta t \left\langle \hat{I}(\bar{r},t) \right\rangle$$

$\alpha(\lambda)$: quantum efficiency (number of photoelectrons/number of incident photons)

$\left\langle \hat{I}(\bar{r},t) \right\rangle$: expectation value of the photon density



The detector measures the number of photons in the cylinder of volume *cSΔt*

•Speed of reading: 15 Mpixels/s, using 64 parallel channels. Maximum efficiency occurs between 500-600 nm.

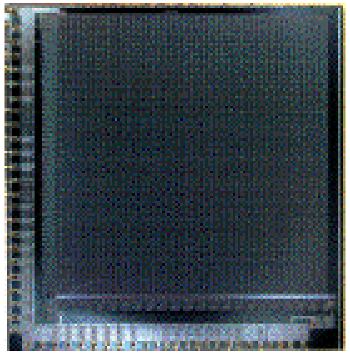
• CMOS APS (*Complementary Metal-Oxide-Semiconductor, Active Pixel Sensor)*

•Initiated at the Jet Propulsion Laboratory (Ca, USA)

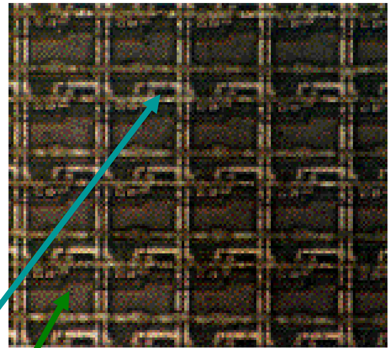
•It captures digital and non digital input signals, which are converted into output digital signals. Pixel size: 5μm

•High speed of reading: 524 Mpixels/s

•The chip structure is based upon silicon technology.



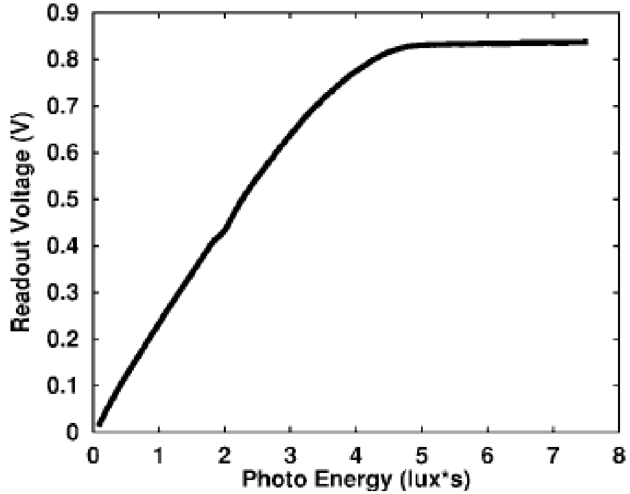
CMOS APS chip structure



A magnified view of the active pixels

Active amplifier

Photodetector



Operational response (*)

[(*) After: S.Y. Ma, L.G. Chen, IEEE J. Solid State Circuits, **14**(1), 1415(1999

II.4.4.- OTHER COMPONENTES

• To operate under an optimal procedure in the process of multiplexing we need scanning devices:

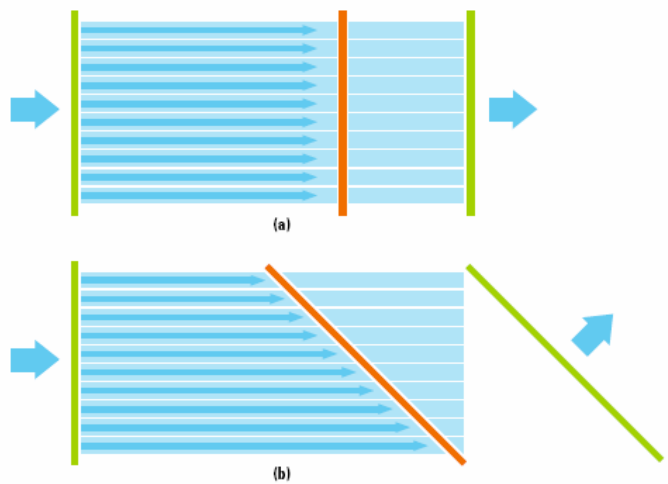
•**Acousto-optics deflectors (*AOD*)**

High speed response (1 μs time scale) . Small deflection angle.

Disadvantage: A frequency shift on the deflected beam is introduced.

•**Mirror deflectors**

•**Liquid crystals (*Optical Phased Arrays, OPA*)**: The deflection is obtained by modulating the phase of the incident wave.



Scheme of functioning of OPA:

a) No voltage is applied. The incident light is transmitted without angular variation.

b) An external voltage is applied. The light is retarded proportional to the applied voltage The emergent light is rotated with respect to the incident one.

II.5.- Holographic techniques for optical data storage of information: multiplexing

Experimental requirements:

1.- Material thickness and diffraction regime:

- Bragg regime has to be determined for recording (writing) and reading.

2.- Dynamic range:

•We require materials with high refractive index modulation: ***$\Delta n \gg 10^{-2}$***
By applying Kogelnik's coupled wave theory, the diffraction efficiency for a holographic transmission grating is:

$$\eta = sen^2\left(\frac{\pi \Delta n d}{\lambda \cos\theta_1}\right)$$

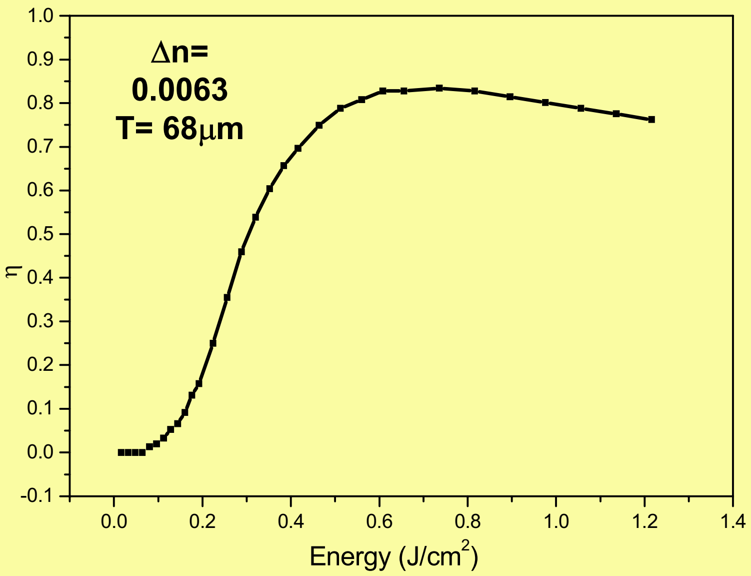
•We define for *N* multiplexed holograms:

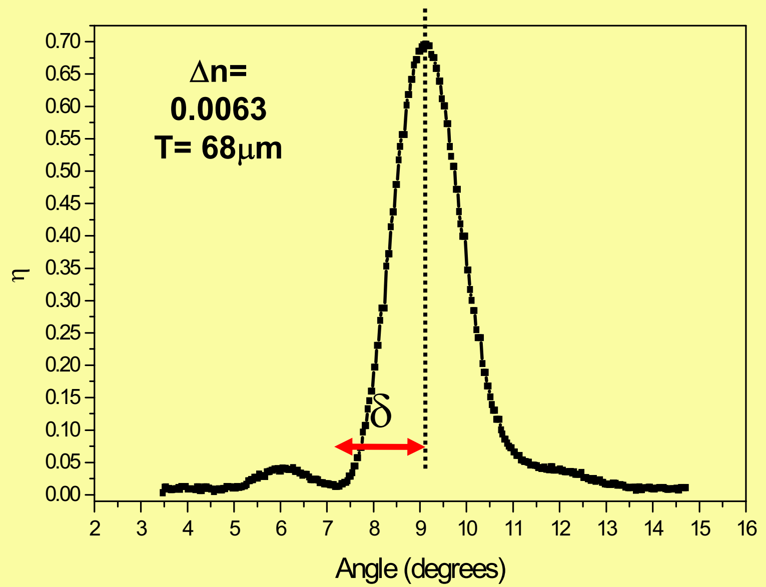
$$\sum_{i=1}^{N}\sqrt{\eta_i} \sim dN\sum_{i=1}^{N}\Delta n_i = d\Delta n; \quad \sum_{i=1}^{N}\sqrt{\eta_i} = M\#; \qquad \eta_i = \left(\frac{M\#}{N}\right)^2$$

M# is related to the diffraction efficiencies of each single multiplexed hologram.

Variation of the first-order diffraction efficiency as a function of the angle of incidence : Angular selectivity

Material: Photopolymer glass: Q = 19. Angular selectivity: 1.76º (*)





With these data and figures one can calculate the thickness of the grating (T) and the refractive index modulation (Δn):

$$\Delta n = 2\, n_0\, Cos(\vartheta_0)\, Sin(\vartheta_0)\, \delta \frac{ArcSin(\sqrt{\eta})}{\sqrt{\pi^2 - \left(ArcSin(\sqrt{\eta})\right)^2}}$$

$$T = \frac{\lambda}{2\, \pi\, n_0\, \delta\, Sin(\vartheta_0)} \sqrt{\pi^2 - \left(ArcSin(\sqrt{\eta})\right)^2}$$

(*) After: M.L. Calvo et al., ICONOLAT/2005, Saint Petersburg, Russia, April 2005.

Q-factor for volume regime

$$Q = \frac{\left|\overline{K}\right|^2 d}{\beta}$$

$\left|\overline{K}\right|$: modulus of the grating vector

d: thickness of the medium

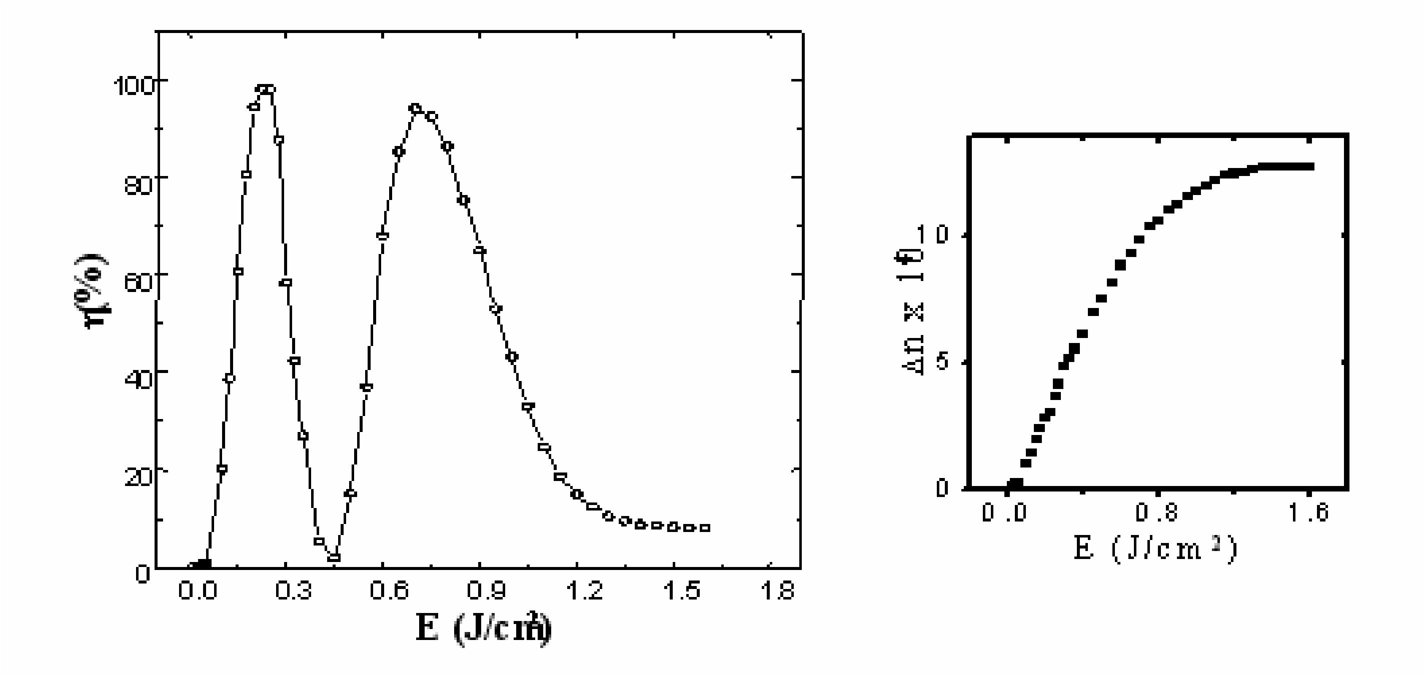
β: modulus of the propagation vector associated to the first order mode

- Condition for volume holographic grating: Q > 10.

CASE OF PHOTOMATERIALS WITH HIGH DYNAMIC RANGE

For recording media presenting high dynamic range, the behavior of the diffraction efficiency as a function of the exposure energy is a periodic function with maxima:

$$\Delta n_k = \frac{\left(k + \frac{1}{2}\right)\lambda \cos\alpha'}{d}$$



After: P. Cheben and M. L. Calvo, Appl. Phys. Lett. **78,** 1490-1492 (2001)

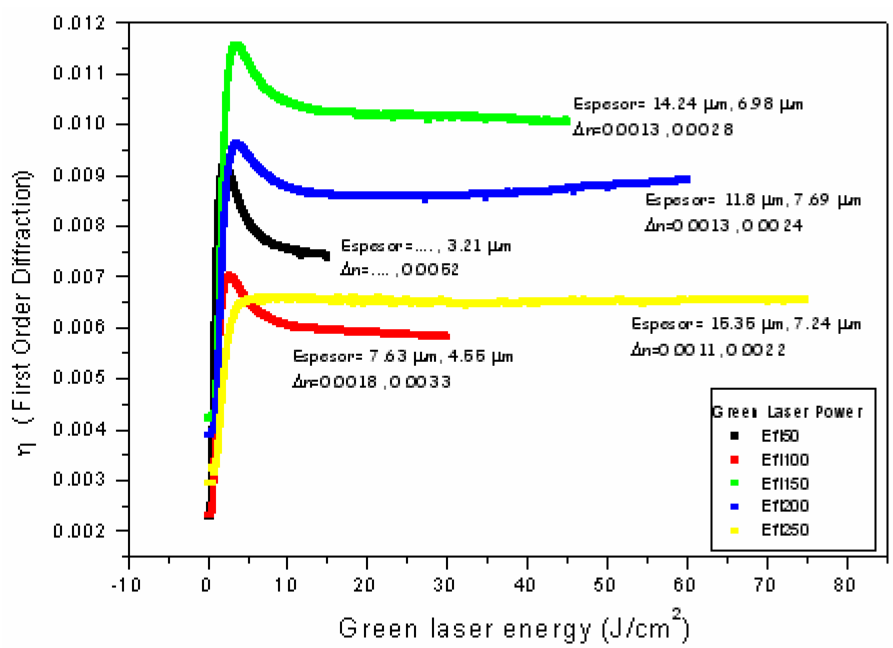
SENSITIVITY

is a function depending on the refractive index modulation and the exposure energy.
can be defined as well as a function of diffraction efficiency.

$$S_1 = \Delta n / E \left[cm^2 / J \right]; \text{ or: } S_2 = \sqrt{\eta} / E \left[cm^2 / J \right]$$

Materials presenting high *S* coefficient require a short time exposure for grating recording.

New generation of photopolymer glasses present high sensitivity (*):



(*): M.L. Calvo et al., "The current status of photopolymer glasses for holographic data storage", Invited conference, ICONO/LAT 2005, San Petersburgo, Rusia. Proc. Conferencia (I. Gurov, ed.)

II.5.- Holographic techniques for optical data storage of information: multiplexing

II.5.1.- Angle multiplexing (in plane, out of plane).

II.5.2.- Peristrophic multiplexing.

II.5.3.- Wavelength multiplexing.

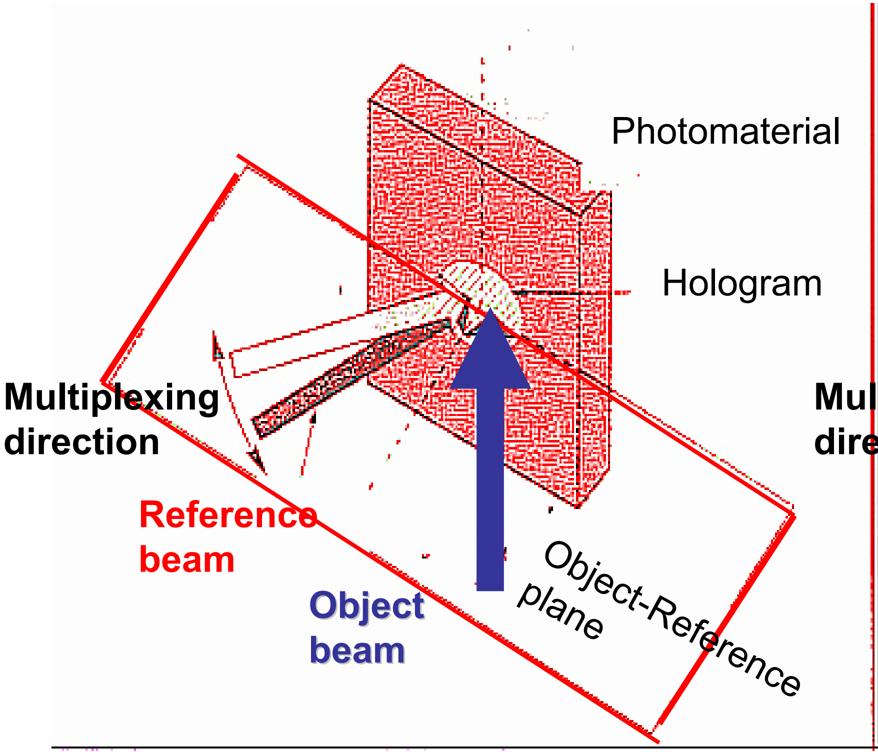
II.4.4.- Phase-coded multiplexing.

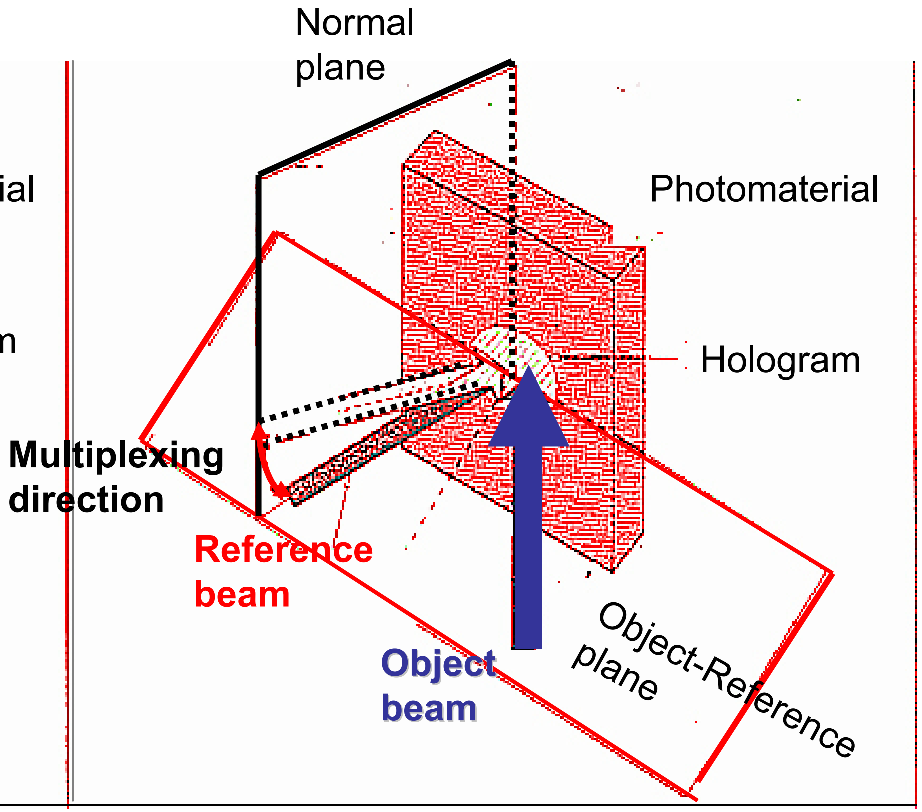
II.5.5.- Shift multiplexing (in plane, out of plane).

II.5.6.- Spatial multiplexing.

II.5.7.- Combination of multiplexing methods.

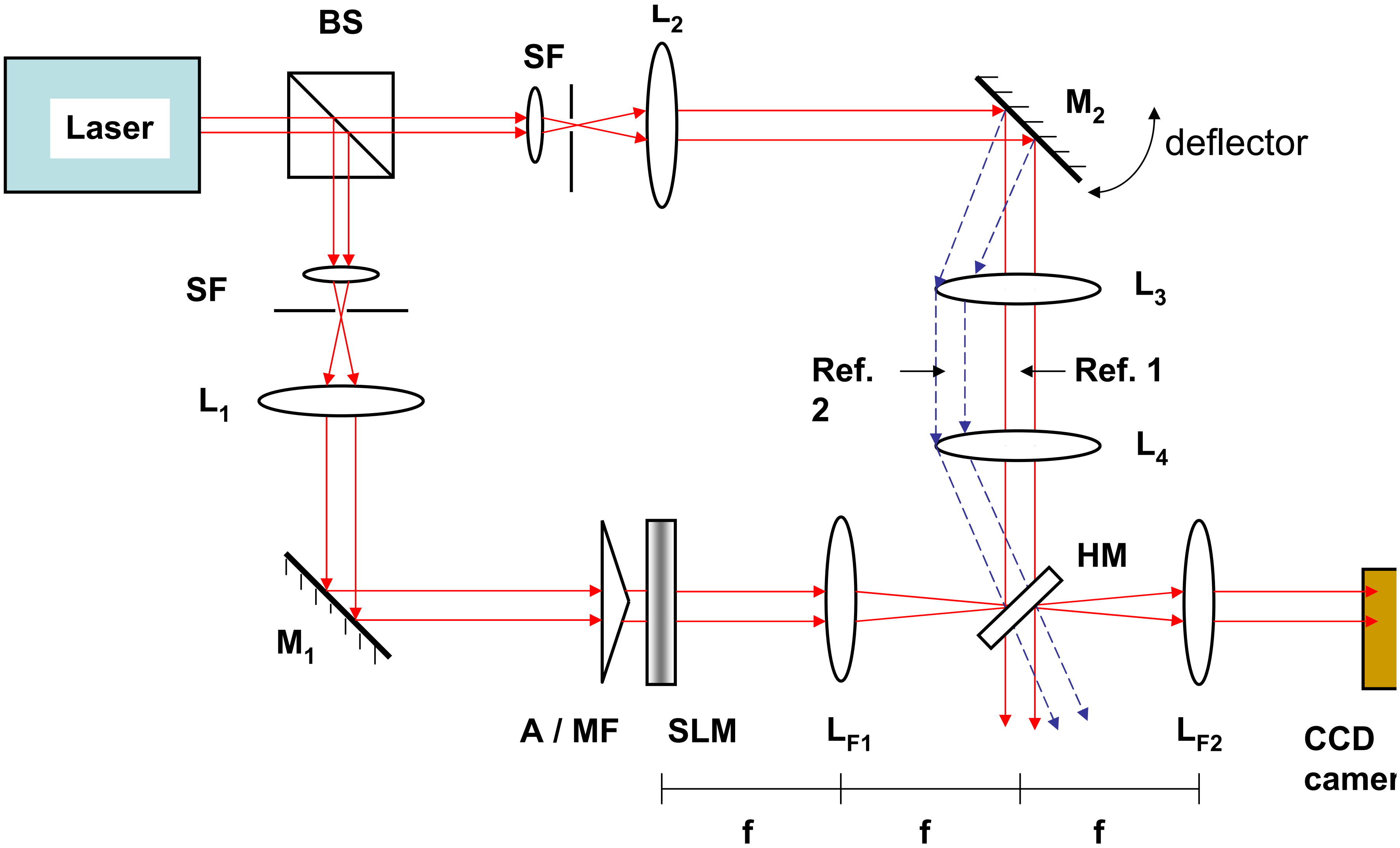
II.5.1.- Angle multiplexing





In-plane multiplexing **Out of plane multiplexing**

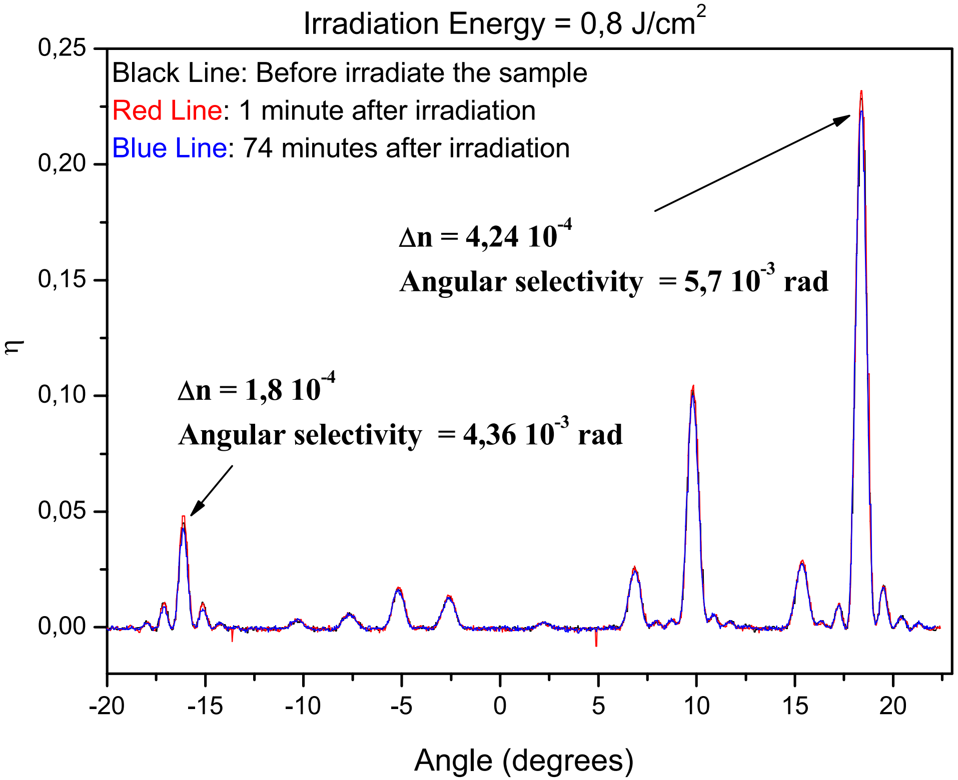
Beams are generally s-polarized.



Schematic diagram for the recording of angle multiplexed holographic gratings

Dynamic angle multiplexing in a modified photopolymer glass (*)

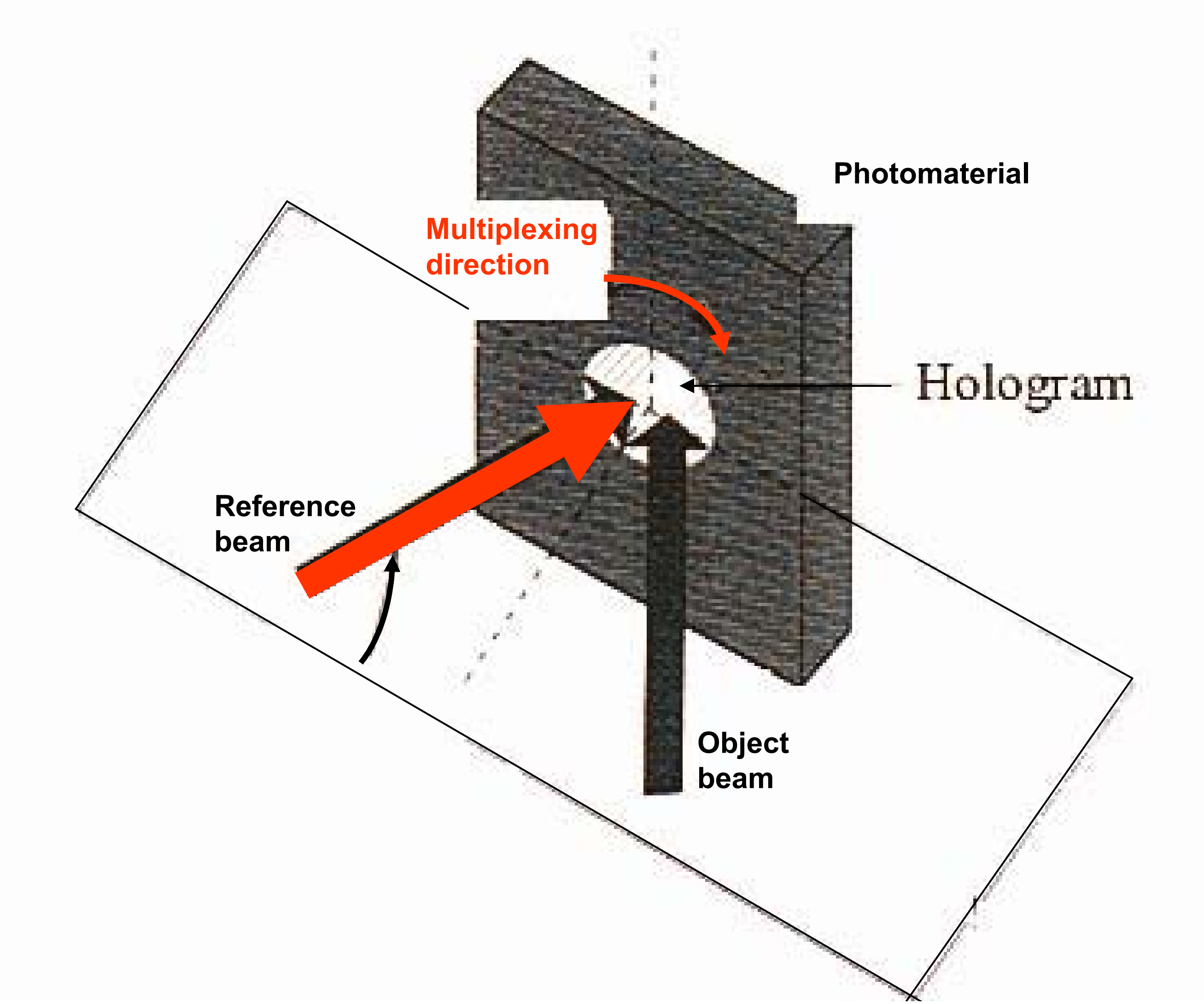
Total number of recorded gratings: 11, sequential temporal recording. Multiplexing fixed with beam irradiation (550 nm, 0.8 J/cm²).



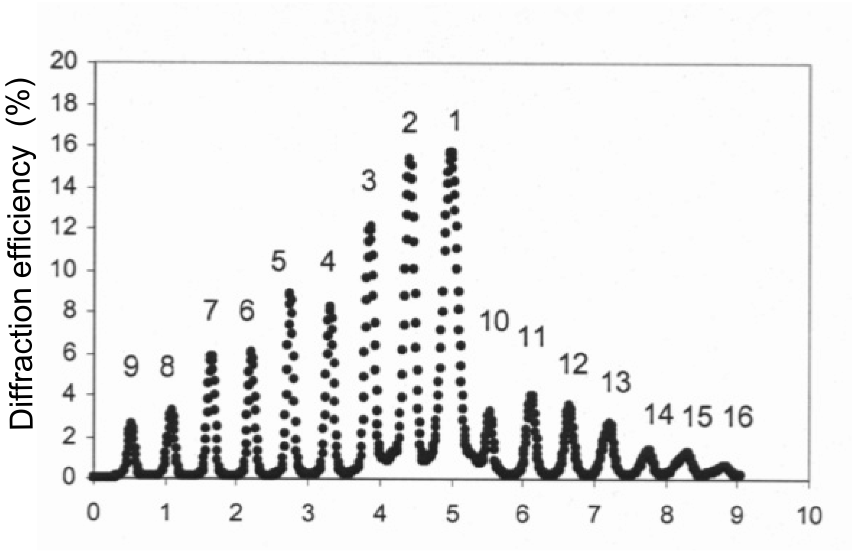
The diffraction efficiencies remain almost invariant after fixing. There is a transfer of energy from gratin recorded at angles < 18º to the grating recorded at 18º. Other aspects: weak scattering, very weak noise gratir angular selectivity. M# = 0.9. Experiments performed with *p*-polarized writing beams show identical results

(*): F. del Monte et al., Adv. Mat. (to be published, 2006)

II.5.2.- Peristrophic multiplexing



Peristrophic multiplexing: Diffraction efficiency



Rotation angle (degrees)

Evolution of the angular selectivity for a multiplexing of 16 holograms recorded in a photopolymer material with 900 μm of thickness

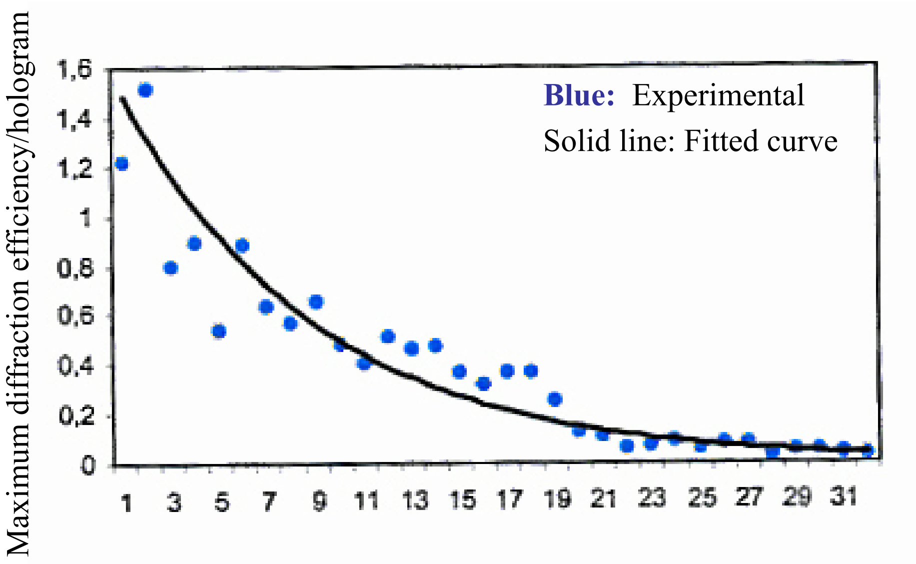
[After: M. Ortuño, PhD Dissertation, Univ. of Alicante, 2004]

Maximum diffraction efficiency gain achieved by each individual hologram. The dynamical range is:

M/# = 1.78

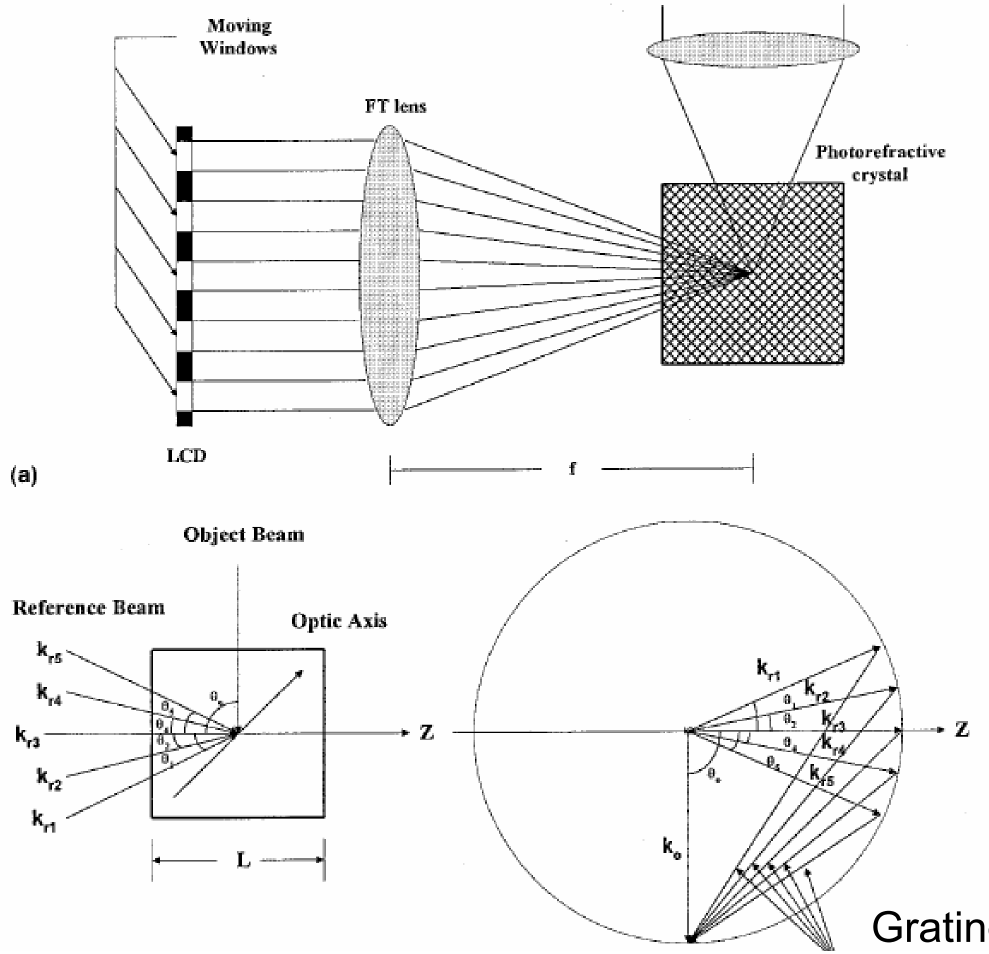
The behavior is a consequence of the consuming of the polimerizable monomer.

[After: M. Ortuño, PhD Dissertation, Univ. of Alicante, 2004]



Number of holograms

Shift Multiplexing (*)



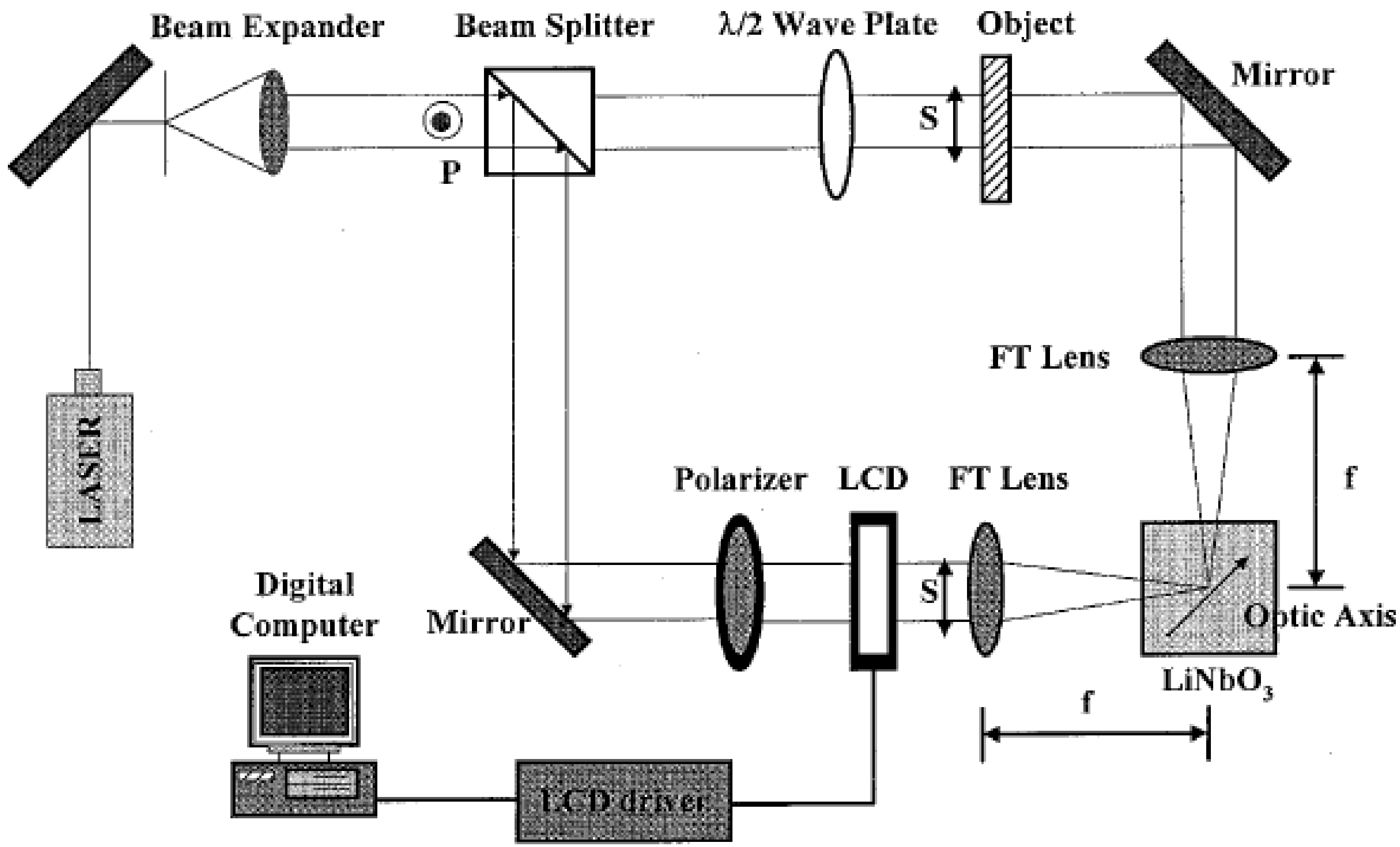
Basic principle

Diagram of grating vectors of the multiplexed gratings

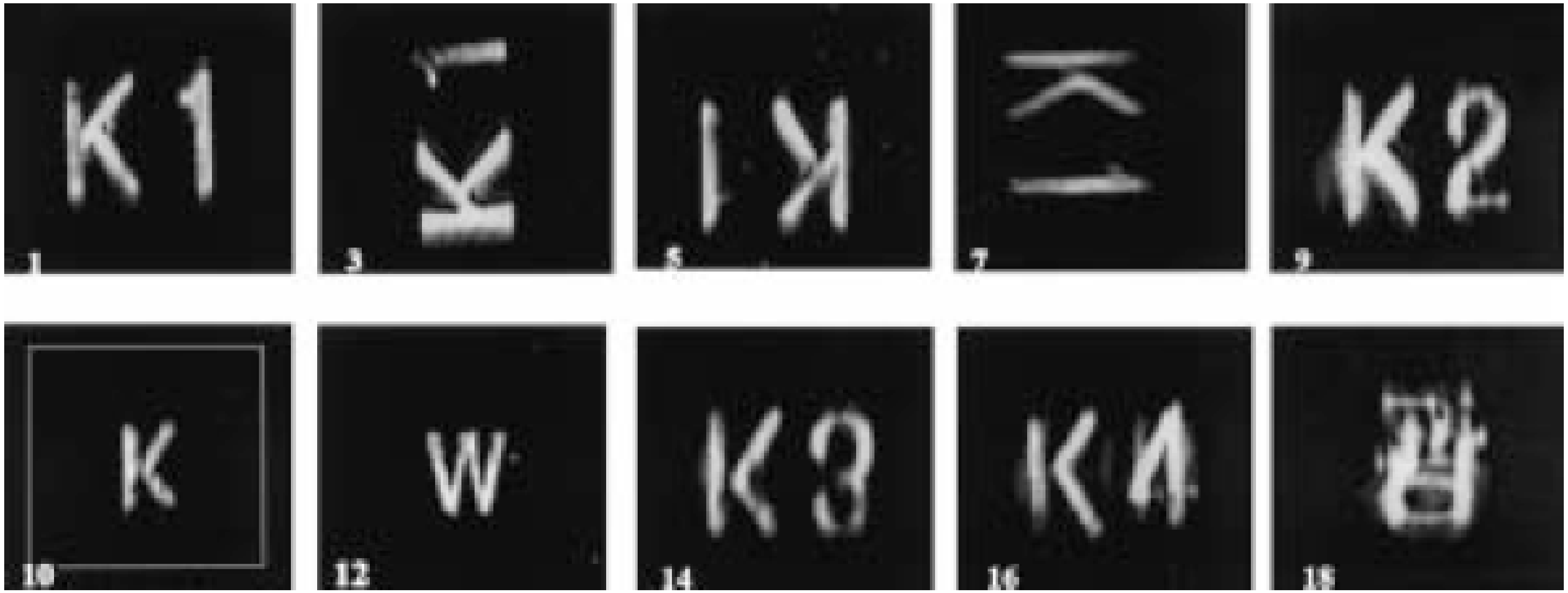
Grating vectors

(*): S.G. Kim et al., “Angular multiplexed holographic memory system based on moving window…”, Opt. Quant. Elect., **32**, 419 (2000)

SCHEME FOR THE EXPERIMENTAL RECORDING
(*Moving Window*)



RECONSTRUCTED MULTIPLEXED IMAGES



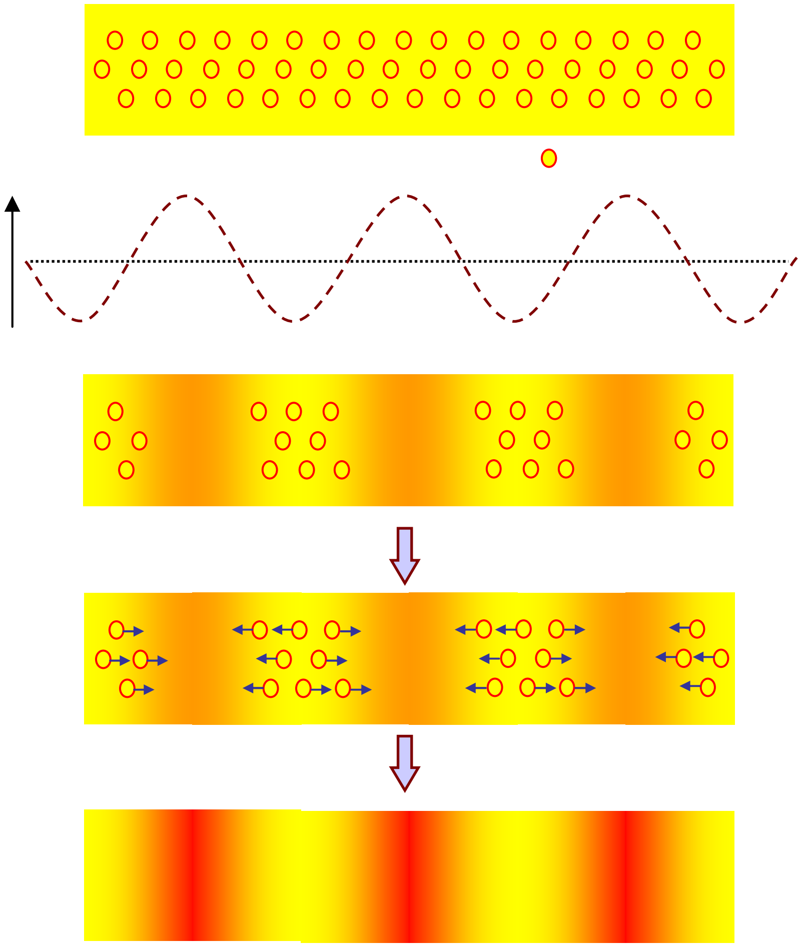
DATA: Focal lens= 12 cm. Angular separation between neighbor pixels: $3{,}5X10^{-4}$ rad. Wavelength: 532,8 nm. Refractive index of the photorefractive crystals: 2,2. Angles of object and reference beams: 45^{o}. Angular selectivity:$1{,}7X10^{-5}$ rad.

The number of holograms is limited by the LCD aperture.

I.6.- Photopolymer materials

- First report on photographic storage in a photopolymer film is due to Joseph Niépce (1822-1827) by photoinduction (*asphalt-based heliography*).
- In 1945 W.E.F. Gates recorded relief images in a metilmetacrilate film.
- D.H. Close et al. from Hughes Aircraft reported in 1969 the recording of holograms in photopolymer materials.
- In 1969 the 1st School in Holography was held in Moscow (Russia) under the initiative of G.V. Skrosky and V.N. Sintsov.
- Volume holographic formation in photopolymer materials was reported early in 1970's (*Colburn*, 1971).
- Commercialization since 1970 has been very active from companies such as E.I. du Pont de Nemours and Polaroid.
- In Spain interesting photopolymers have been developed at the University of Alicante (*Fimia* et al. since 1990).
- High range of applications: Holograms for security, Head-up-Displays, holographic filters, holographic couplers and even artistic holograms.

SCHEME FOR DESCRIBING MONOMER DIFFUSION
(Colburn and Haines mechanism)*



•Formation of a permanent spatial modulations of refractive index within the volume of a photo-polymerizable material by monomer diffusion. It follows the diffraction pattern generated by interference of two coherent laser beams.

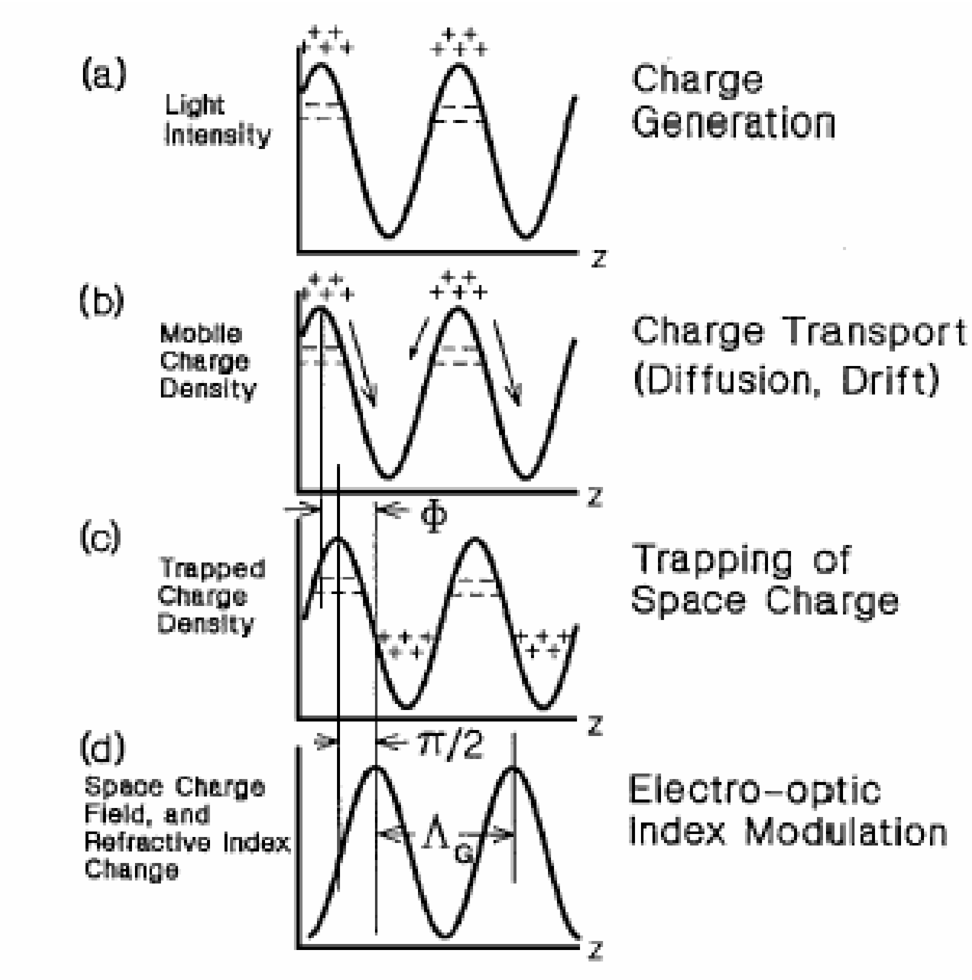
Lighter colours (e.g., yellow) represent low refractive index fringes and darker colours (e.g., orange) high refractive index fringes.

(*): W.S. Colburn, K.A. Haines, Appl. Opt., **10**(7), 1636(1971)

II.7.- Photorefractive (PR) polymers

- The first proven PR polymer was made in 1990 (*Ducharme et al.)*
- The mechanism is the same as in conventional PR inorganic crystals: (a) photoconductivity and (b) refractive index dependence with the electric field.
- But specific components are required in order to obtain the non-linear behavior.
- Important properties:
  - (a): High index modulation can be reached via electro-optic effect.
  - (b) Dynamic (erasable) hologram materials.
  - c) Two and four wave mixing processes are plausible.
  - d) New PR polymer materials are required to be tested having the PR effect as the main phenomenon present in the mechanism of the refractive index modulation.

PHOTOREFRACTIVE GRATING FORMATION (*)



(a): The charge generation occurs at maxima in light intensity.

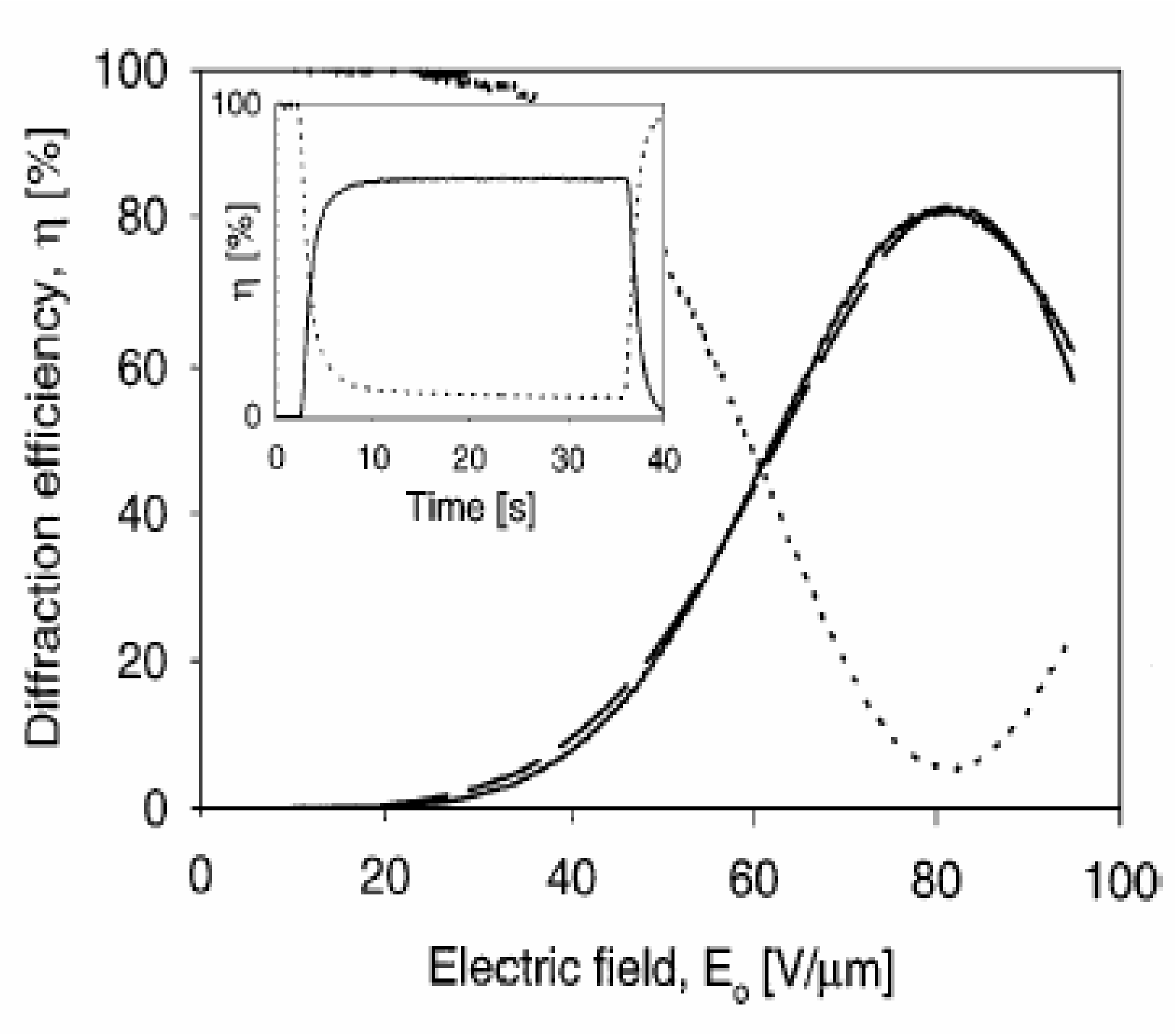
(b) Holes migrate by diffusion in the presence of external fields.

c) The charges build up at the light intensity maxima.

(d): A space-charge field is created leading to a refractive index modulation in an electro-optically active material.

(*) G. C. Valley, M.B. Klein, Opt. Eng., **22**, 704(1983)

Diffraction efficiency as a function of the external applied electric field



- FWM scheme is applied.
- Solid line: Diffraction efficiency.
- Dashed line: Measured direc transmission of beam 3.
- Inset shows grating writing and erasing dynamics.
- Dark decay is of great importance for holographic data storage applications.

II.8.- Sol-Gel Holographic recording materials

- Virtually no thickness/size limitations, monoliths several cm thick
- Minimized shrinkage due to a rigid glassy binder
- Low effective index of porous binder
- Excellent monomer diffusion due to interconnected porosity
- Improved thermal and chemical stability and mechanical properties
- Easy polishing for high optical quality
- Practically unlimited range of compositions with tailored properties.
- Mixing of inorganic and organic components at the nanometer scale, in virtually any ratio
- Easy fabrication and low cost (in low mass production scheme)
- And more …

Some antecedents of the sol-gel techniques

- Silica gels are commonly found in nature in the form of opals and agates
- The preparation of a synthetic silica gel was first reported by ***J.J. Ebelmen*** 160 years ago (1845, Paris, France).
- The first sol-gel patent was made by Schott Glaswerk (Jena, 1939) to produce antireflecting and scratch resistant glass surfaces. Commercialized in 1959.
- In 1962, a British patent for sol-gel technique was issued in nuclear industry for preparation of UO_2 and ThO_2 microspheres.
- The first meeting on “Glasses and Glass from Gels” was held in Padova (Italy) in 1981.
- In 1996, Cheben et al. reported the first organically modified sol-gel material suitable for recording of volume holograms.
- In 2000, Cheben et al. reported a photorefractive grating with refractive index modulation of 0.002 and a two-beam coupling gain of 444 cm^{-1} recorded in an organically modified permanently poled sol-gel glass
- In 2001, first high refractive index modulation and sensitivity reported to date in a photopolymerizable material of 1 mm thickness (Cheben et al).

Sol-gel: Glasses and ceramics from molecular precursors

- **Definition of the process:** Construction of a **silica glass** by progressive chaining of monomer units (Ebelmen's procedure).

- 1.- **Molecular precursors**: Metallic alcoxydes: In this case $Si(OR)_4$
The Si atom is surrounded by **groups OR**. R: methyl CH_3 or ethyl C_2H_5

- 2.- **Hydrolysis:** $Si\left(OR\right)_4 + xH_2O \rightarrow Si\left(OR\right)_{4-x}\left(OH\right)_x + xROH$

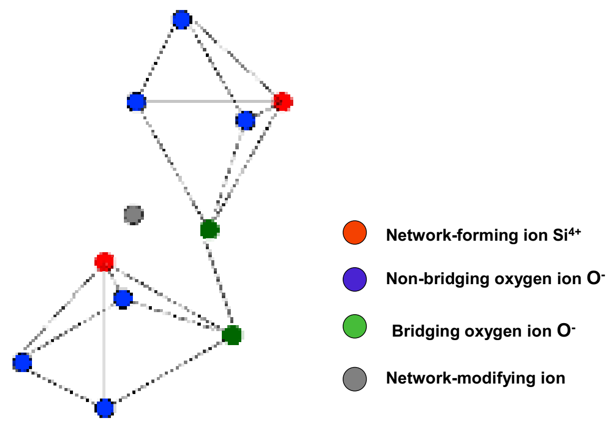
- 3.- **Polycondensation:**

$$2Si(OR)_{4-x}(OH)_x \rightarrow (OH)_{x-1}(OR)_{4-x}\text{-}Si\text{-}O\text{-}Si\text{-}(OR)_{4-x}(OH)_{x-1} + H_2O$$

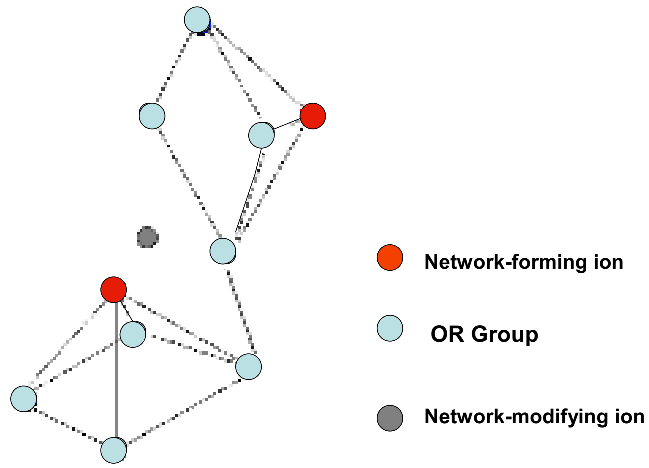
- 4.- **Final product (formation of oxygen bridges):**

$$2Si(OR)_{4-x}(OH)_x + H_2O \rightarrow Si_2O(OR)_{6-2x}(OH)_{2x} + 2ROH$$

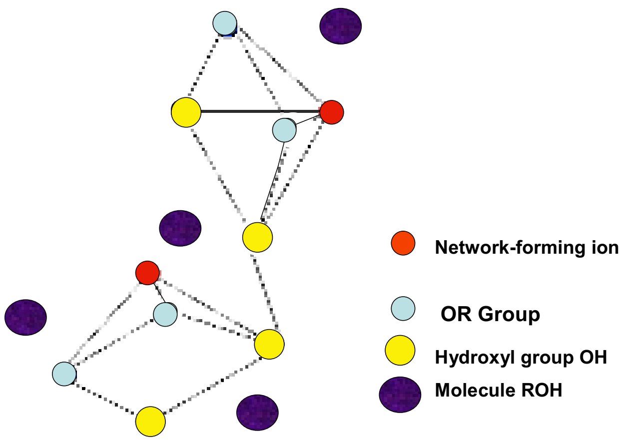
A simple 3-D model with two molecules for the structure of a glass



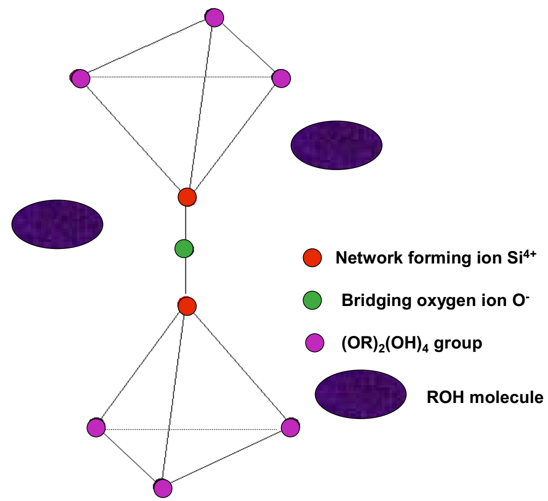
Molecular precursors



Molecular precursors + Hydrolisis (i.e. $2H_2O$)



A NEW MOLECULE IS FORMED: CHAINED SILICATE



II.8.1.- Hybrid organic-inorganic material

- **Class I composites**

  Weak interaction between organic and inorganic components (van der Wals contact, hydrogen bonds or electrostatic)

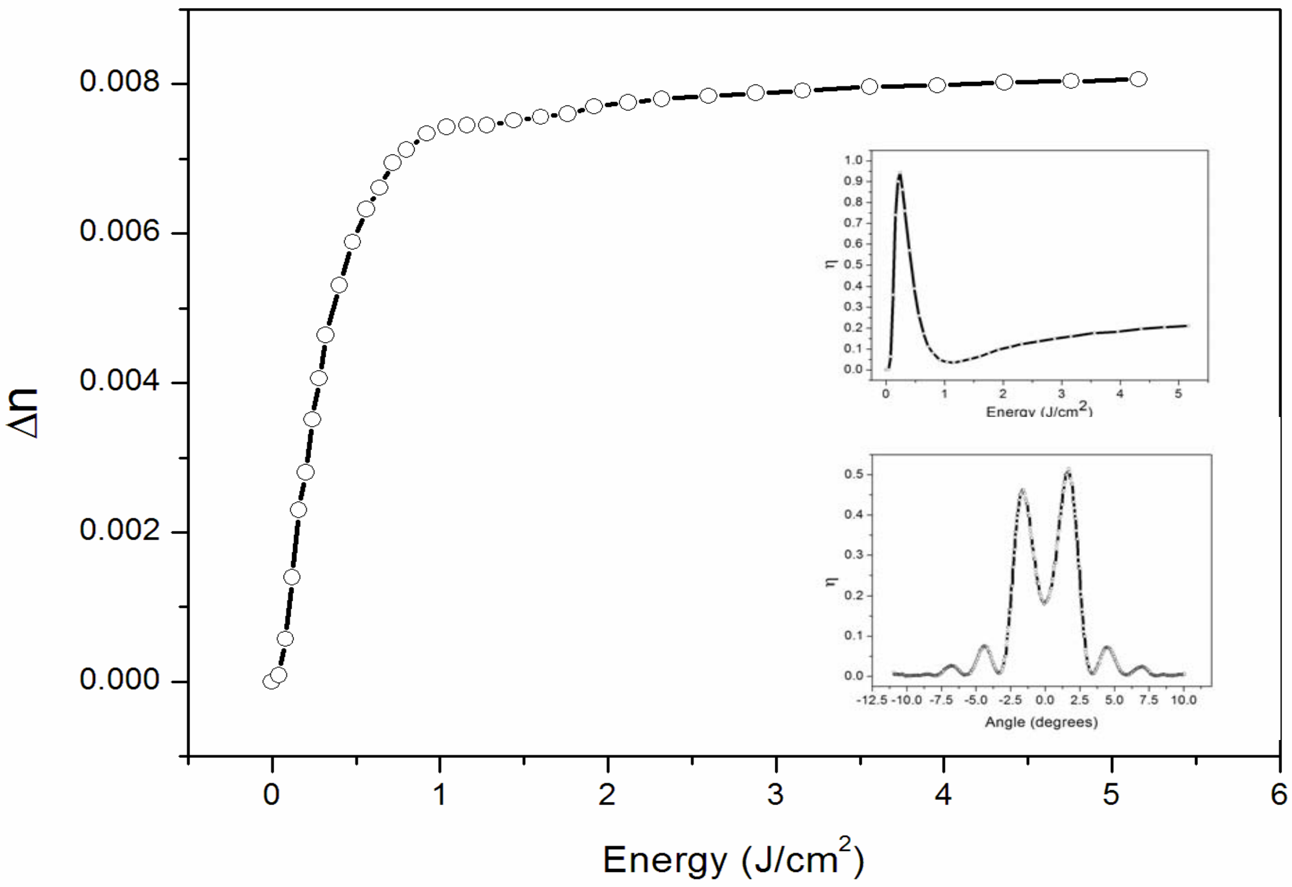
  - Photopolymerizable sol-gel glasses

- **Class II composites (Subjects of our current interest)**

  At least a fraction of organic and inorganic components are linked through strong (covalent or ion-covalent) bonds

  - Photopolymerizable sol-gel glasses
  - Photorefractive sol-gel glasses
  - Thick film ormosil

Over-modulation in a modified photopolymer glass



After: O. Martínez Matos et al., Proc. ICO Topical meeting on Optoinformatics/Photonics 2006, Saint Petersburg (to be published).

SOME APPLICATIONS

- Security systems

  Encryption
- Optical waveguides technology:

  SOI platforms, wavelength demultiplexing

  Sensor configurations
- Holography:

  Waveguide holograms

  Holographic storage
- Laser technology:

  Holographic optical elements as collimators
- Reflection gratings (coated)

I.9.- Conclusions

- Considerations of some of the limitations of the current photomaterials for holographic data storage provides an indication to issues to be addressed in future researches.
- Two main problems should be mentioned:

1) Issues related to fabrication :

- Samples thickness and dimensional stability.
- Behavior as volume holographic gratings.
- Studies of different configurations and geometries.

2) Issues related to mechanics :

- Sensitivity or response per unit time.
- Fixing mechanisms for avoiding partial erasing during the recording process.
- Possibilities of two (or more) color writing.

II.9.- Conclusions (cont.)

- Modeling efforts should continue in order to understand and to predict abilities and performances.

- Multidisciplinary efforts:

  In areas as: Chemistry, material sciences, informatics, optics, photonic devices, in order to achieve high performances, low cost devices and operational flexibility.

II.10.- REFERENCES

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