Zenithal bistable liquid-crystal gratings as tunable beam splitters

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5th Workshop on Liquid Crystals for Photonics, Erice, Italy, Sept. 3-6, 2014

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Overview

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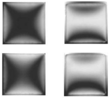

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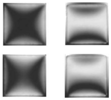

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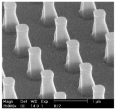

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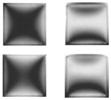

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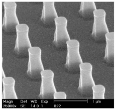

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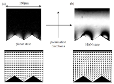

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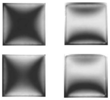

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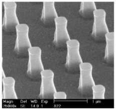

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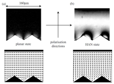

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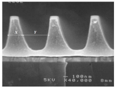

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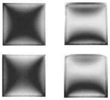

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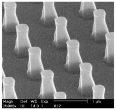

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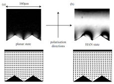

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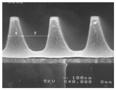

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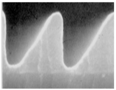

[Proc. SID 51.2, 1626 (2006)]

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- Zero idle consumption, high tolerance to mechanical stress, no image sticking, fabrication in TN-LCD production lines...

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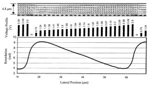

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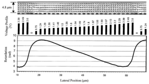

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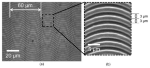

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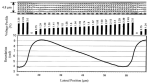

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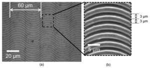

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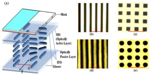
Rewritable photoalignment pattern



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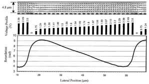

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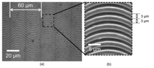

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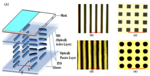

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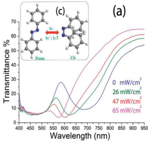
All-optical azo-dye switching



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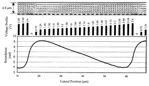

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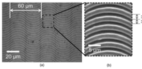

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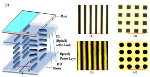

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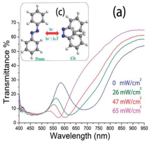

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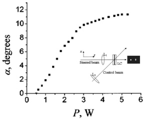
All-optical non-linear switching



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- Can leverage on the mature LCD/ZBD fabrication technology.
- Need for rigorous numerical tools: a) LC orientation in bistable devices, b) optical/diffraction studies, c) Optimization procedure to achieve target results.

The Q-tensor model for LC studies

- The orientation of the nematic molecules is expressed via the 3×3 symmetric tensor $\mathbf{Q}$, which is the traceless part of the second moment of the probability density function matrix.

$$\mathbf{Q} = \begin{pmatrix} q_1 & q_2 & q_3 \\ q_2 & q_4 & q_5 \\ q_3 & q_5 & -q_1 - q_4 \end{pmatrix}$$

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- In the general case of biaxial solutions, it can be decomposed into two directors and two order parameters,

$$\mathbf{Q} = S_1 (\mathbf{n} \otimes \mathbf{n}) + S_2 (\mathbf{m} \otimes \mathbf{m}) - \frac{1}{3} (S_1 + S_2) \mathbf{I}$$

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- The free energy in the LC bulk is expressed as

$$F = \iiint_V F_b \, dV = \iiint_V \left(F_{\mathrm{th}} + F_{\mathrm{el}} + F_{\mathrm{em}}\right) \, dV$$

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- The free energy is minimized via the solution of the Euler-Lagrange equations

$$\sum_{j=1}^{3} \frac{\partial}{\partial x_j} \left(\frac{\partial F_b}{\partial q_{i,j}} \right) - \frac{\partial F_b}{\partial q_i} = \gamma_1^* \frac{\partial D}{\partial \dot{q}_i},$$

for $i = 1...5$, where $q_{i,j} = \partial q_i / \partial x_j$, x_j being the unit vectors of the three-dimensional cartesian system. The r.h.s. of (9) describes the dynamic evolution of the $\mathbf{Q}$ tensor via the dissipation function $D = \mathrm{tr}(\dot{\mathbf{Q}}^2)$, where $\dot{\mathbf{Q}} = \partial \mathbf{Q} / \partial t$. The term γ_1^* is related to the LC rotational viscosity γ_1 via $\gamma_1^* = \gamma_1 / \left(4 S_{\mathrm{exp}}^2 \right)$

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- The thermotropic energy F_{th} is expressed via a Taylor expansion around **Q**

$$F_{\mathrm{th}} = a\,\mathrm{tr}\left(\mathbf{Q}^2\right) + \frac{2b}{3}\mathrm{tr}\left(\mathbf{Q}^3\right) + \frac{c}{2}\left(\mathrm{tr}\left(\mathbf{Q}^2\right)\right)^2$$

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- The elastic energy is described by

$$F_{\text{el}} = \sum_{i,j,k=1,2,3}\left[\frac{L_1}{2}\left(\frac{\partial Q_{ij}}{\partial x_k}\right)^2 + \frac{L_2}{2}\frac{\partial Q_{ij}}{\partial x_j}\frac{\partial Q_{ik}}{\partial x_k}\right] + \sum_{i,j,k,l=1,2,3}\left[\frac{L_6}{2}Q_{lk}\frac{\partial Q_{ij}}{\partial x_l}\frac{\partial Q_{ij}}{\partial x_k}\right]$$

The elastic parameters L_i are related to the Frank elastic constants K_{ii} via the expressions $L_1 = \left(K_{33} - K_{11} + 3K_{22}\right)/\left(6S_{\text{exp}}^2\right)$, $L_2 = \left(K_{11} - K_{22}\right)/S_{\text{exp}}^2$, and $L_6 = \left(K_{33} - K_{11}\right)/\left(2S_{\text{exp}}^3\right)$.

The Q-tensor model for LC studies

- The electrostatic energy in the presence of an external electric field is given by

$$F_{\mathrm{em}} = -\int \mathbf{D} \cdot d\mathbf{E},$$

The displacement field is given by the constitutive equation

$$\mathbf{D} = \varepsilon_0 \tilde{\varepsilon}_r \mathbf{E} + \mathbf{P}_s,$$

For nematic materials the dielectric tensor is given by

$$\tilde{\varepsilon}_r = \Delta\varepsilon^* \mathbf{Q} + \bar{\varepsilon}\mathbf{I},$$

where $\Delta\varepsilon^* = (\varepsilon_{\parallel} - \varepsilon_{\perp})/S_{\mathrm{exp}}$ is the scaled dielectric anisotropy and $\bar{\varepsilon} = (\varepsilon_{\parallel} + 2\varepsilon_{\perp})/3$.

The Q-tensor model for LC studies

- The spontaneous polarization $\mathbf{P}_s$ derives from the flexoelectric effect:

$$P_i = p_1 \sum_{j=1,2,3} \frac{\partial Q_{ij}}{\partial x_j} + p_2 \sum_{j,k=1,2,3} Q_{ij} \frac{\partial Q_{jk}}{\partial x_k},$$

where $p_1 = (e_{11} + e_{33})/(2S_{\mathrm{exp}})$ and $p_2 = (e_{11} - e_{33})/(2S_{\mathrm{exp}}^2)$ are terms depending on the classical flexoelectric polarazation coefficients e_{11} and e_{33}, as in

$$\mathbf{P}_s = e_{11}\left(\nabla \cdot \mathbf{n}\right)\mathbf{n} + e_{33}\left(\nabla \times \mathbf{n}\right) \times \mathbf{n},$$

where $\mathbf{n}$ is the nematic director.

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In this work, the nematic material of choice is E7, characterized by:

- Thermotropic coefficients: $a = -0.3 \times 10^5$ J/m^3, $b = -1.5 \times 10^5$ J/m^3, and $c = 2.5 \times 10^5$ J/m^3
- Elastic coefficients: $K_{11} = 10.3$ pN, $K_{22} = 7.4$ pN, and $K_{33} = 16.48$ pN
- Dielectric properties: $\varepsilon_{\parallel} = 18.6$, $\varepsilon_{\perp} = 5.31$, $e_{11} + e_{33} = 15$ pC/m, and $e_{11} - e_{33} = 10$ pC/m
- Rotational viscosity: $\gamma_1 = 282.8$ mPa

Diffraction efficiency calculation in optical gratings

The efficiencies for the various diffraction modes in the proposed liquid-crystal gratings are calculated as follows:

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2. The optical transmitted field $\mathbf{E}^t$ is recorded at a constant plane in the grating's superstratum
3. The $x-$component of $\mathbf{E}^t$ is expanded in a 1-D Floquet series according to

$$E_x^t(x, y = y_0) = \sum_m E_{x,m}^t \, e^{-j\beta_m y},$$

where $\beta_m = \beta_0 + 2\pi m/p_0$, $\beta_0 = (2\pi n_g/\lambda_0)\sin(\theta_{\rm inc})$ being the polymer wavenumber projection in the direction of periodicity (x-axis) for the general case of oblique incidence at an angle $\theta_{\rm inc}$.

Diffraction efficiency calculation in optical gratings

4. The amplitudes $E^t_{x,m}$ are obtained from orthogonality considerations with an integration over a grating period

$$E^t_{x,m} = \frac{1}{p_0} \int_{y=y_0} E^t_x(x, y_0) e^{j\beta_m y} dx.$$

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5. Finally, the total diffraction efficiency for each diffraction mode is calculated by

$$\mathrm{DE}_m = \frac{P_m}{P^i} = \frac{\left|E^t_{x,m}\right|^2}{\left|E^i_x\right|^2 \left|\cos\theta_m\right|},$$

where P^i, E^i_x are the power and amplitude of the incident electric field, respectively, and $\cos\theta_m$ is given by

$$\cos\theta_m = \frac{\sqrt{(k_0 n_g)^2 - \beta_m^2}}{k_0 n_g},$$

where $k_0 = 2\pi/\lambda$ is the free space wavenumber.

Liquid Crystal Zenithal Bistable Beam Splitters

- Structural layout: sinusoidal and triangular gratings

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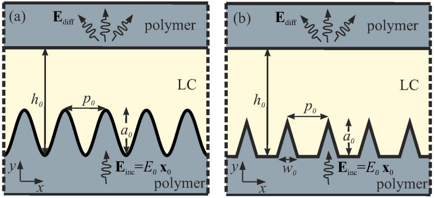

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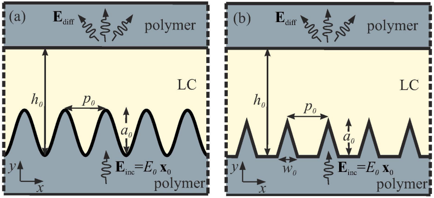

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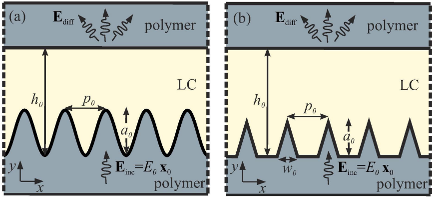

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- The nematic material is E7.
- Target wavelength: $\lambda_0 = 633$ nm.

- Objective: minimize diffraction in one of the LC stable states and achieve equal power splitting (two to five beams) in the complimentary state.

Liquid Crystal Zenithal Bistable Beam Splitters

- The sinusoidal ZB-LC grating shows two stable states with low (HAN) and high (VAN) tilt angle values.

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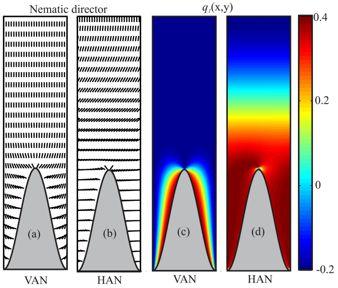

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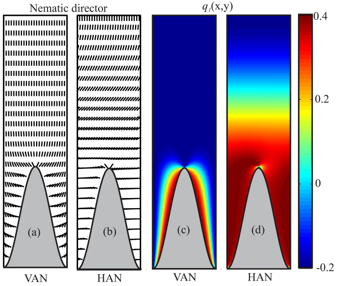

- Defects are formed at the peak and trough of the grating for the HAN state.
- The modulation of the q_i elements, and thus refractive index, is significantly lower in the HAN state.
- HAN state: in the vicinity of the grating LC molecules are aligned mainly along the grating vector ($q_1(x, y)$ obtains high values).

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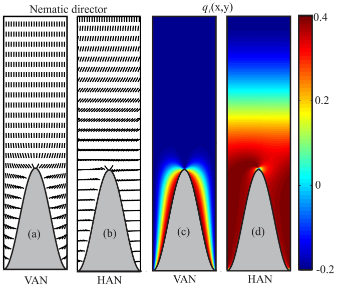

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- Matching condition: we opt for a polymer material whose refractive index n_p is equal to the LC extraordinary index $n_e = 1.73$ for E7 at 633 nm. This minimizes diffraction in the HAN state.

Liquid Crystal Zenithal Bistable Beam Splitters

- What about the VAN state? We implement a Nelder-Mead optimization algorithm and scan the parameter space of the geometrical features of the grating (p_0, a_0).

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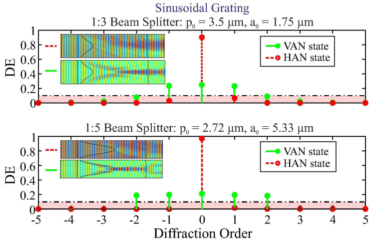

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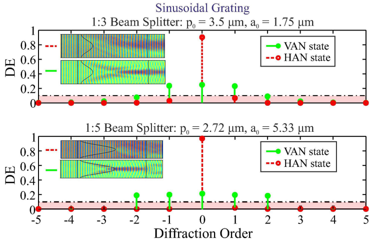

- A threshold of 10% is set for the diffraction efficiency of undesired modes.
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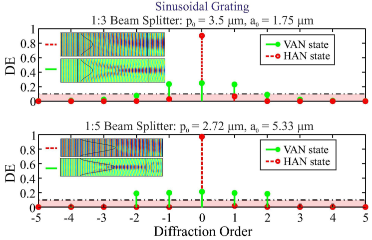

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- Efficient beam splitting in three and five beams is demonstrated for the optimized grating designs.

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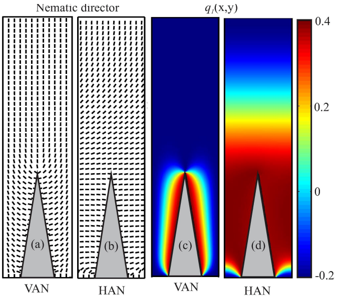

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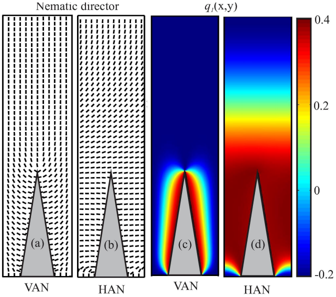

- Defects are observed in both LC states.
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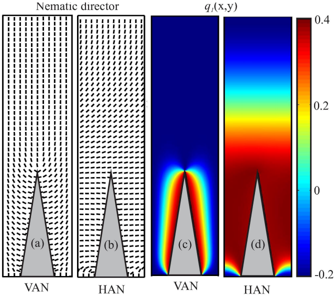

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- The same optimization method is implemented: the parameter space is composed by the grating pitch p_0, the height a_0 and the filling factor $f = w_0/p_0$.

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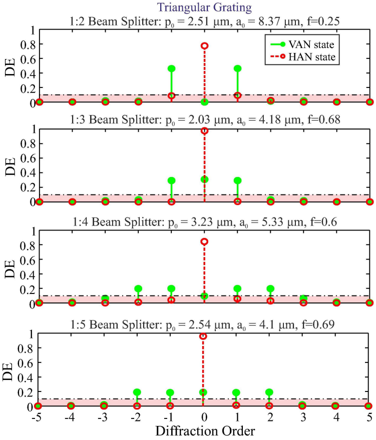

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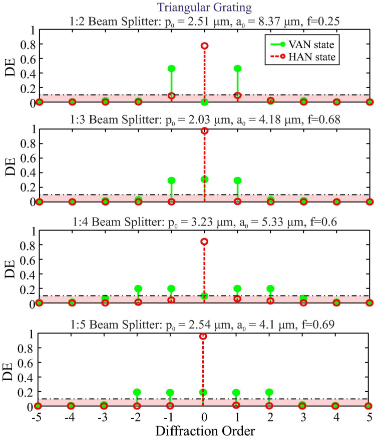

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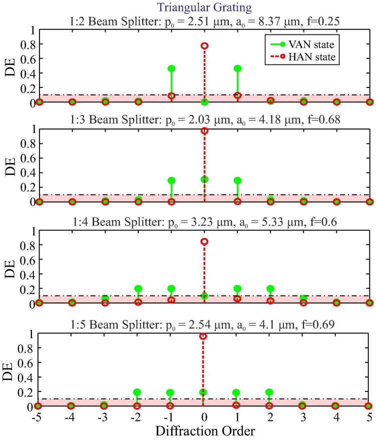

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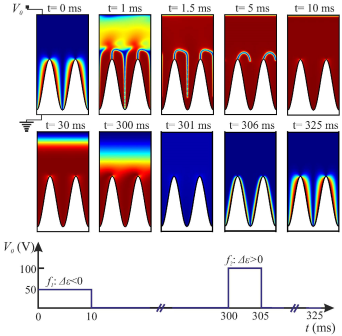

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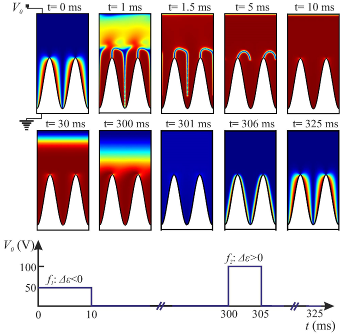

- Control voltage is applied across the the $1 \rightarrow 3$ sinusoidal grating via two ITO films.
- The grating is initially in the VAN state.
- A 10−ms 50 V pulse is applied at a frequency $f_1 : \Delta\varepsilon < 0$ at $t = 0$, followed by a 5−ms 100 V pulse at $f_1 : \Delta\varepsilon > 0$ at $t = 300$ ms.

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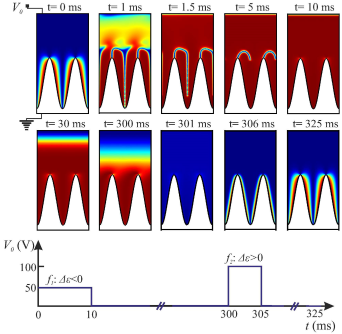

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- Among the two transitions, the VAN to HAN is much slower (100s of ms).

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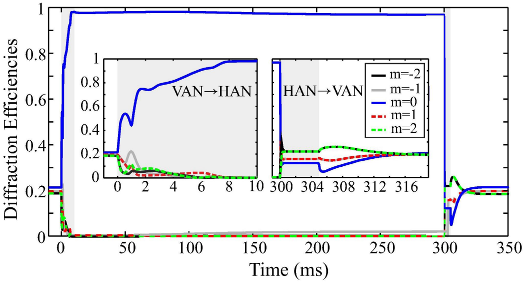

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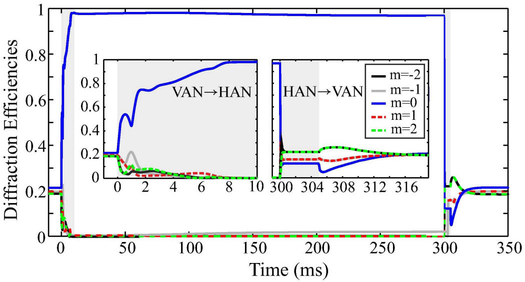

- The intermediate states during the VAN to HAN transition are non-diffracting.
- The overall switching speed of the device is governed by the HAN to VAN dynamics, in the range of 10 ms.

Liquid Crystal Zenithal Bistable Beam Steerers

- Structural layout: blazed triangular grating

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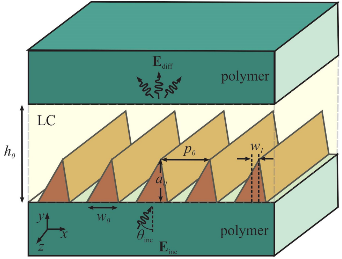

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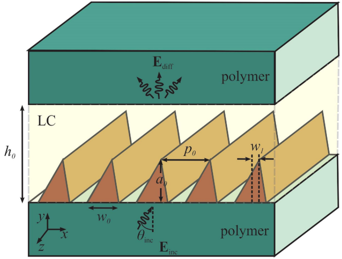

- Grating parameters: pitch p_0, height a_0, base w_0, blazing offset w_1.
- The nematic LC is E7. The polymer index n_p is matched to the LC extraordinary index n_e.
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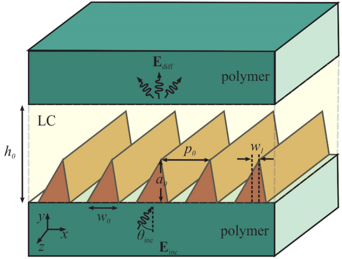

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- The nematic LC is E7. The polymer index n_p is matched to the LC extraordinary index n_e.
- Target wavelength: $\lambda_0 = 633$ nm.

- Objective: minimize diffraction in the HAN state and maximize it in the VAN state along a single diffraction order.

Liquid Crystal Zenithal Bistable Beam Steerers

- Optimized design for 633 nm: $p_0 = 1.6$ µm, $a_0 = 5.54$ µm, $w_0 = 1.26$ µm, and $w_1 = 0.65$ µm.

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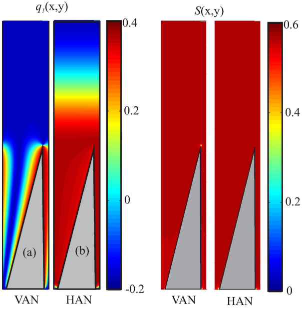

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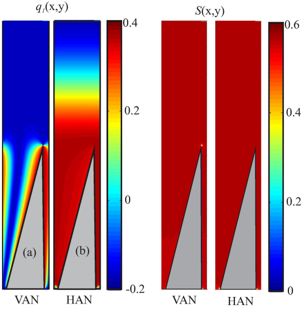

- The HAN state shows very small index variation along the grating vector.
- Lower local values of the nematic order parameter with respect to the bulk value (0.6) indicate the presence of point defects.

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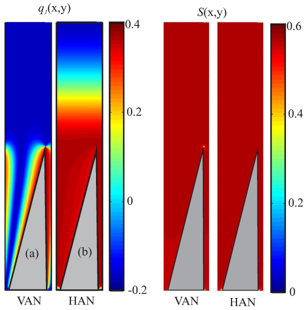

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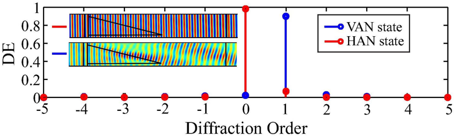

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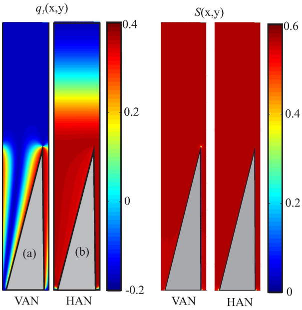

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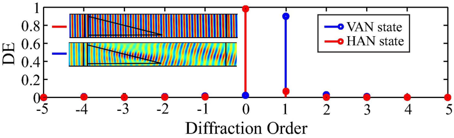

- Diffraction efficiencies for the HAN and VAN states: 99% ($m = 0$) and 91% ($m = 1$).

Liquid Crystal Zenithal Bistable Beam Steerers

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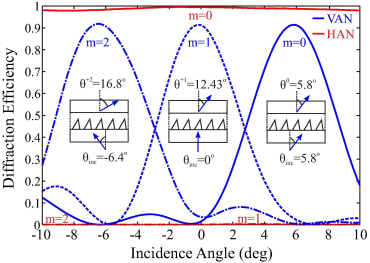

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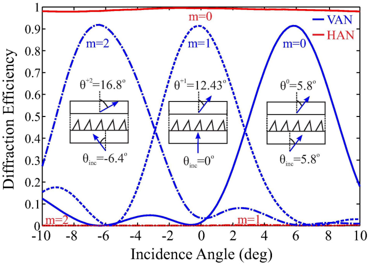

- Angle of incidence is varied from -10 to 10°.
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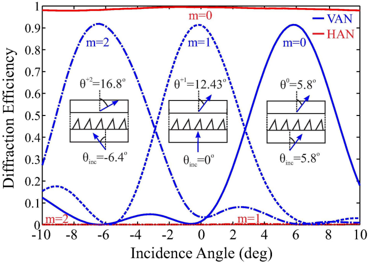

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- For $\theta_{\text{inc}} = -6.4^{\circ}$ efficient diffraction is achieved towards the $m = 2$ mode.

Liquid Crystal Zenithal Bistable Beam Steerers

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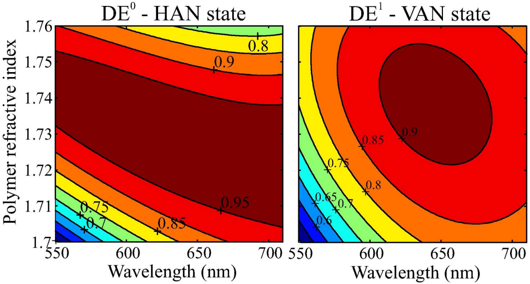

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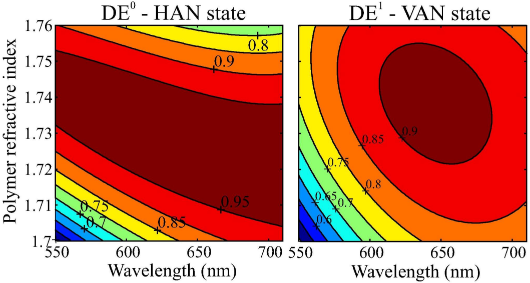

- Diffraction efficiencies calculated in a $[n_p, \lambda_0]$ parameter space.
- E7 index dispersion taken into account (Cauchy model).

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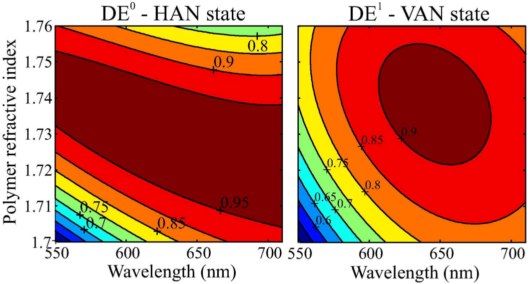

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- The non-resonant nature of the diffraction mechanism leads to increased robustness/broad bandwidths.

Conclusions

1. Switchable beam splitting/steerer demonstrated in zenithal bistable liquid crystal gratings

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Acknowledgments

Financial Support

This work was supported by the Italian Ministry of Foreign Affairs, Directorate General for the Country Promotion and by the European Union (European Social Fund-ESF) and Greek national funds through the Operational Program Education and Lifelong Learning of the National Strategic Reference Framework (NSRF) Research Funding Program THALES Reinforcement of the interdisciplinary and/or inter-institutional research and innovation (Project ANEMOS).