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Photonic vortex lattice based on dielectric polarization textures

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Abstract: The existence of polar vortex textures in strained nanoscale ferroelectric materials has been recently experimentally verified. As shown in this contribution, such materials offer a new route to study chiral, topological, and photonic systems. We show that, in the THz regime, the polar vortex lattice couples simultaneously to electric and magnetic field components leading to the formation of a photonic vortex lattice with particular dispersion. We discuss the spectral and mode properties of the formed photonic textures and discuss possible utilization in optoelectronics.

Materials with polar ordering are shown in [1]-[4] to exhibit chiral and vortex lattice textures (*e.g*., as schematically depicted in Fig. 1a) that can be controlled by external stimuli, *e.g*., by switching the underlying ferroelectric polarization [3]. We address in this contribution the characteristics of the photonic modes that are hosted in such dielectric structures. Analytical considerations, supported by rigorous self-contained material-specific numerical simulations [5] for the electromagnetic scattering, evidence the polarization-dependent optoelectronic modes and the emergence of photonic band-gaps (Fig.1b). In particular, we demonstrate how the ferroelectric vortex lattice enables a coupling to electric and magnetic fields simultaneously resulting in a novel type of photonic vortex lattice with particular dispersion that we analyze for a wide class of ferroelectric layered heterostructures. The proposed method based on the coupled differential equations presents an efficient numerical tool for the analysis of other types of structured ferroelectrics and gives a full picture of the coupling behavior of the electromagnetic waves with the vortex of electric dipole arrays.

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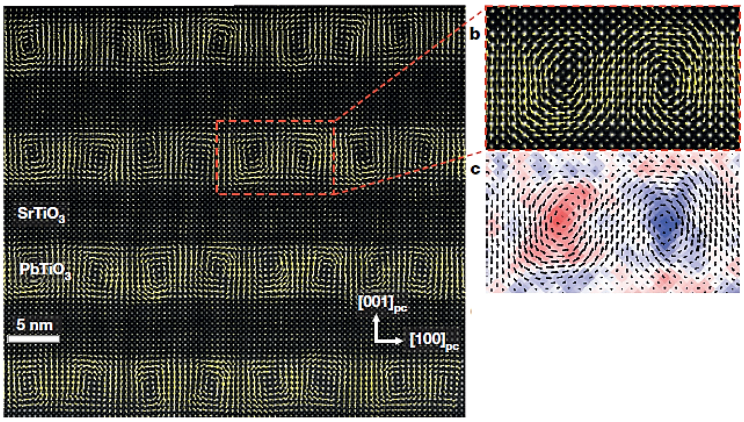

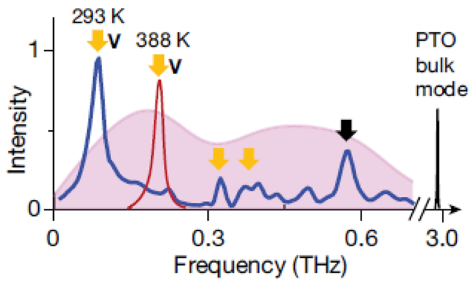

Yadav et al. Nature **530**, 198 (2016); Li *et al.* Nature **592**, 376 (2021)
Sánchez-Santolino *et al.* Nature **626**, 529 (2024)

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this talk

- vortex lattice photonic properties
- dispersion and scattering

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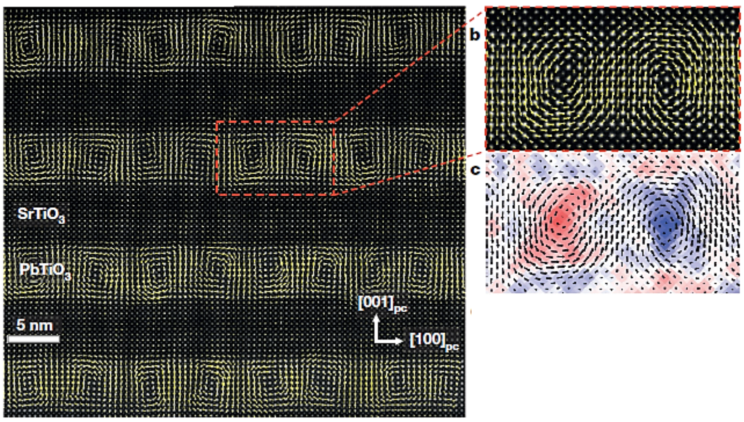

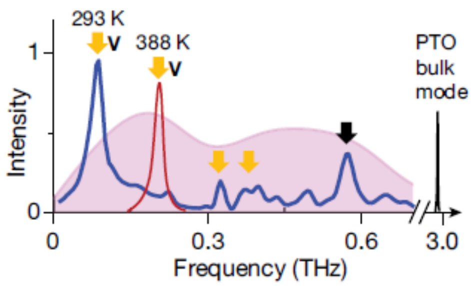

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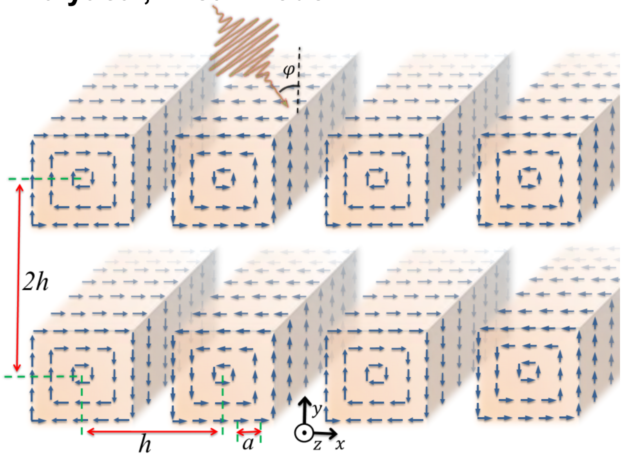
Methods of study

Analytical, linear model

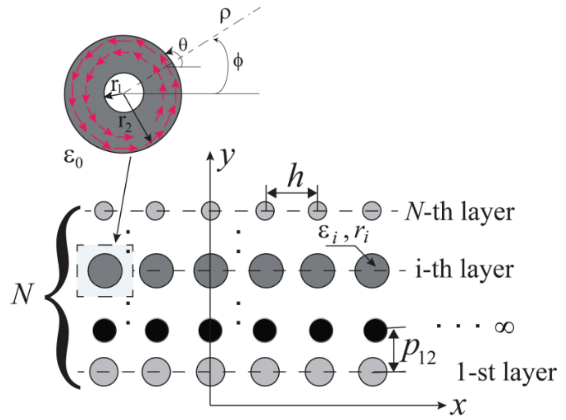


Bloch mode analysis

infinite along *y* and *x* and invariant along *z direction*

analytical approximate method

Full numerical model



Transition (T-matrix) approach combined with lattice sums technique

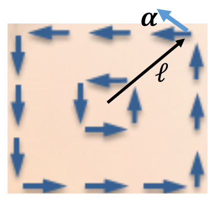
infinite along *x*-axis, finite along *y* and invariant along *z* direction

Full-wave rigorous modal solver

Dielectric response

EM fields induce coupled rotary dynamics with angle $\boldsymbol{\alpha}$ of local dipole d

$$\hat{\mathbf{I}}\ddot{\boldsymbol{\alpha}} = \mathbf{d}\times\mathbf{E} + \mu_0 \boldsymbol{\ell}\times\dot{\mathbf{d}}\times\mathbf{H}, \qquad \dot{\mathbf{d}} = \dot{\boldsymbol{\alpha}}\times\mathbf{d}$$



Maxwell equations in non-collinear ordered dipolar media

$$\nabla\times\mathbf{E} = -\mu_0\dot{\mathbf{H}}, \qquad \nabla\times\mathbf{H} = \varepsilon_0\dot{\mathbf{E}} + \dot{\mathbf{P}}/a^3, \qquad \mathbf{P} = \mathbf{d}/a^3$$

linearization→ dielectric response

$$\mathbf{d} = \mathbf{d_0} + \delta\mathbf{d}(t),\ \delta\mathbf{d} = \boldsymbol{\alpha}\times\mathbf{d_0} \quad \Longrightarrow \quad \hat{\mathbf{I}}\delta\ddot{\mathbf{d}} = -\mathbf{d_0}\times\mathbf{d_0}\times\mathbf{E}$$

$$\mathbf{P} = \delta\mathbf{d}/a^3 = \varepsilon_0\hat{\boldsymbol{\chi}}^{(1)}\boldsymbol{E}$$

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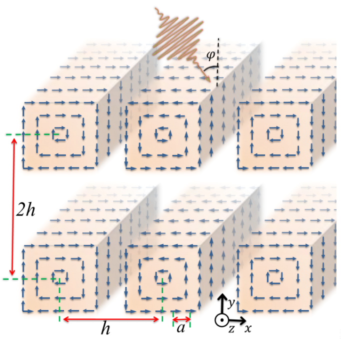
susceptibility tensor

linearization→ $\mathbf{P} = \delta\mathbf{d}/a^3 = \varepsilon_0 \hat{\boldsymbol{\chi}}^{(1)} \boldsymbol{E}$ (no gyrotropic response in 1. order)

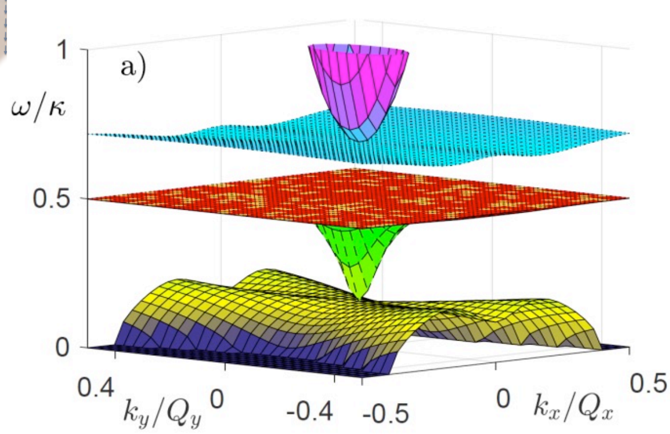
$$\hat{\boldsymbol{\chi}}^{(1)} = \begin{pmatrix} -\frac{(d_{0y})^2}{\varepsilon_0 \omega^2 I_z} & \frac{d_{0x} d_{0y}}{\varepsilon_0 \omega^2 I_z} & 0 \\ \frac{d_{0x} d_{0y}}{\varepsilon_0 \omega^2 I_z} & -\frac{(d_{0x})^2}{\varepsilon_0 \omega^2 I_z} & 0 \\ 0 & 0 & -\frac{(d_{0y})^2 + (d_{0x})^2}{\varepsilon_0 \omega^2 I_x} \end{pmatrix}$$

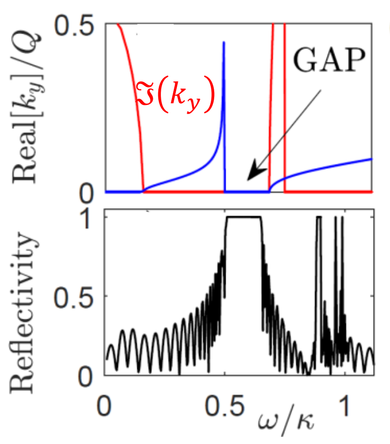
Transverse magnetic (TM) wave



$$\Delta\mathbf{E} - \nabla(\nabla \cdot \mathbf{E}) = -\omega^2 \mu_0 \hat{\boldsymbol{\epsilon}} \mathbf{E}$$

$$Q \equiv 2\pi/h, \ \kappa \equiv \sqrt{d_0^2/(a^3 I_z \epsilon_0)}$$





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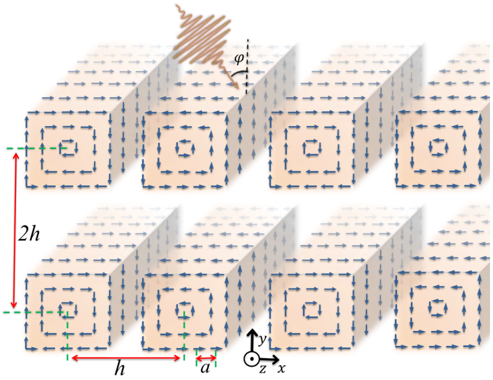
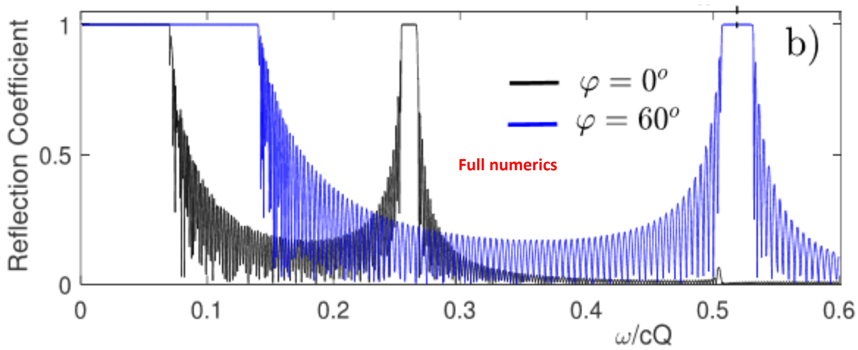
Transverse electric (TE) wave

$$\Delta \mathbf{E} - \nabla(\nabla \cdot \mathbf{E}) = -\omega^2 \mu_0 \hat{\boldsymbol{\epsilon}} \mathbf{E}$$

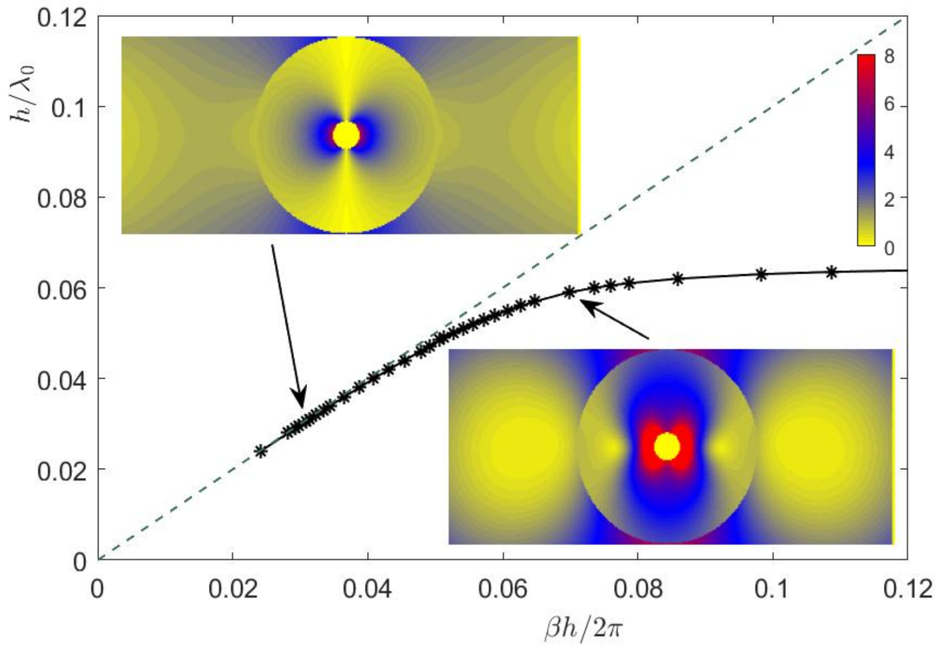
$$\left[\frac{\omega^2}{c^2} - \frac{(\kappa')^2}{2c^2} - k_x^2 - k_y^2\right] E_{\mathbf{k}}^z = \frac{(\kappa')^2}{\pi c^2}\left[E_{\mathbf{k}+\mathbf{Q_y}}^z + E_{\mathbf{k}-\mathbf{Q_y}}^z\right]$$

$$\kappa \equiv \sqrt{d_0^2/(a^3 I_z \epsilon_0)} \qquad \kappa' \equiv \kappa\sqrt{I_z/I_x}.$$





Vortex-polariton: non-linear regime



Frequency vs. propagation constant β along x axis with mode distribution $\sqrt{E_x^2 + E_y^2}$ in the unit cell at excitation frequencies: $h/\lambda_0 = 0.034$ and 0.060. λ_0 is free-space wavelength.

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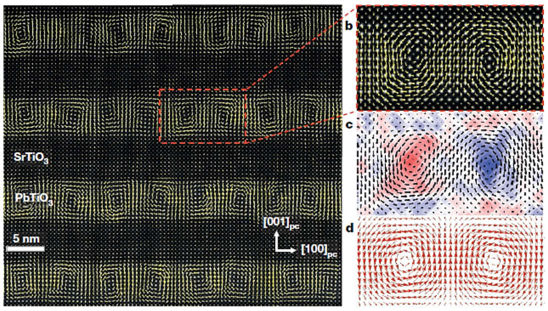
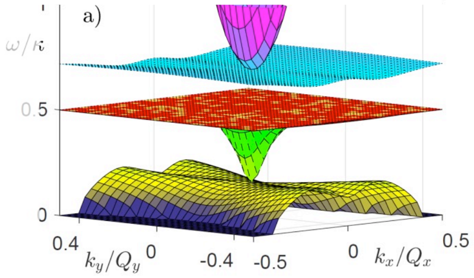
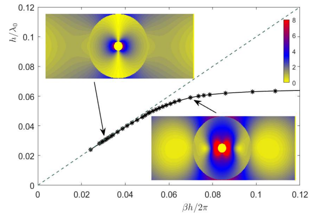
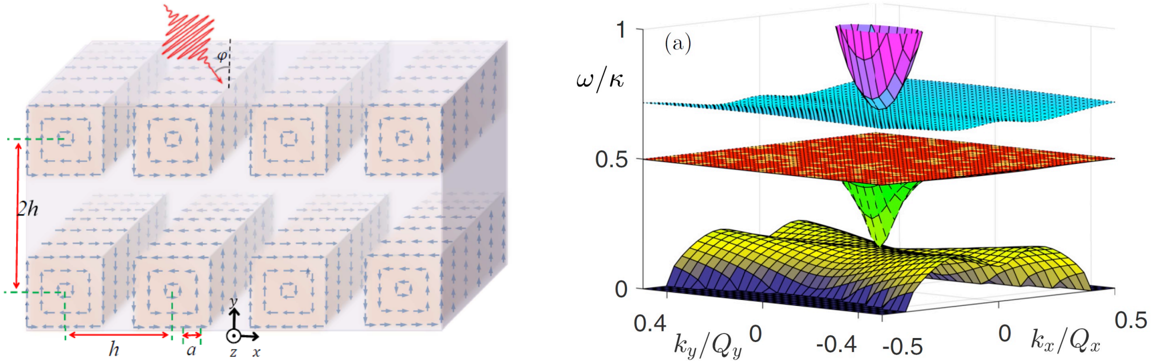


Dispersion E-field and T-tunable

Polaritonic effect and nonlinearity at vortex-lattice interface







(a) (b)

Figure 1: Schematics of ferroelectric vortex lattice which we use for the photonic simulations. The arrows show the local ferroelectric polarization direction that curl to form neighboring vortices with opposite chiralities. The equilibrium distances between the centers of the vortices along the *x*- and the *y*-axes are *h* and 2*h*, respectively. The distribution of the local polarization along the *z* direction is uniform. The distance between the neighboring electric dipoles is *a*. We consider an electromagnetic wave incident with an inclined angle of φ. (b) Dispersion of the TM (H_z, E_x, E_y) modes calculated from the linear set of Bloch mode equations [5] where the wavevector is measured in units of $Q_x = 2\pi/h$ and $Q_y = \pi/h$. The frequency unit in this example is approximately $\kappa = 2\pi$ THz. More details can be found in [5].

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