ФОТООТКЛИК ДВУМЕРНЫХ ПОЛУПРОВОДНИКОВ НА СТРУКТУРИРОВАННОЕ ИЗЛУЧЕНИЕ

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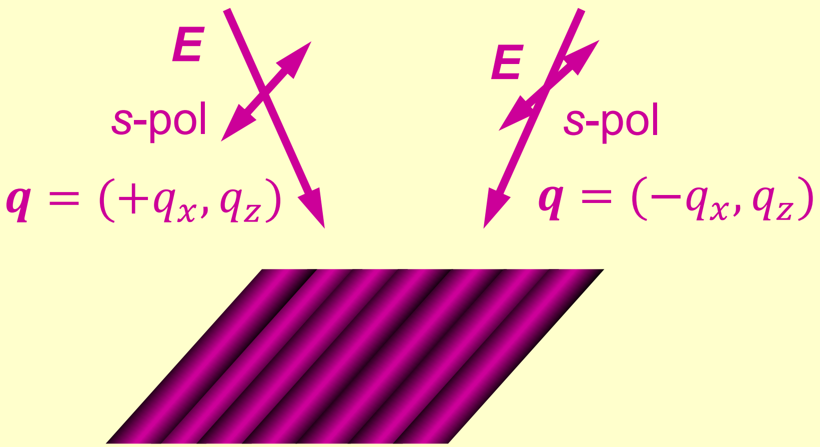
ФТИ им. А.Ф. Иоффе, Санкт-Петербург

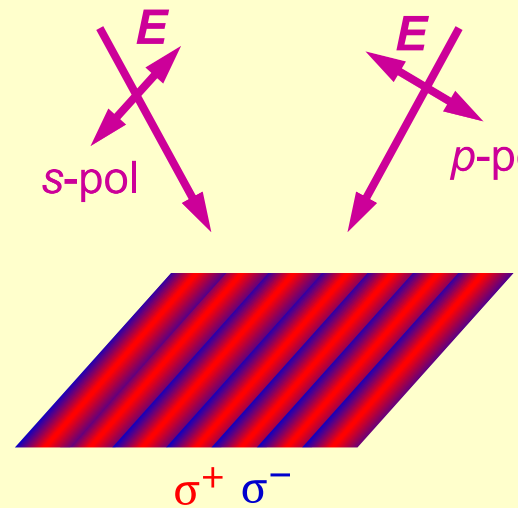
Зимняя школа по физике полупроводников, Зеленогорск, 25 февраля – 1 марта 2026

STRUCTURED RADIATION

From intensity or polarization gratings to beams carrying orbital angular momentum (twisted radiation) and fields with fully controlled spatiotemporal structure



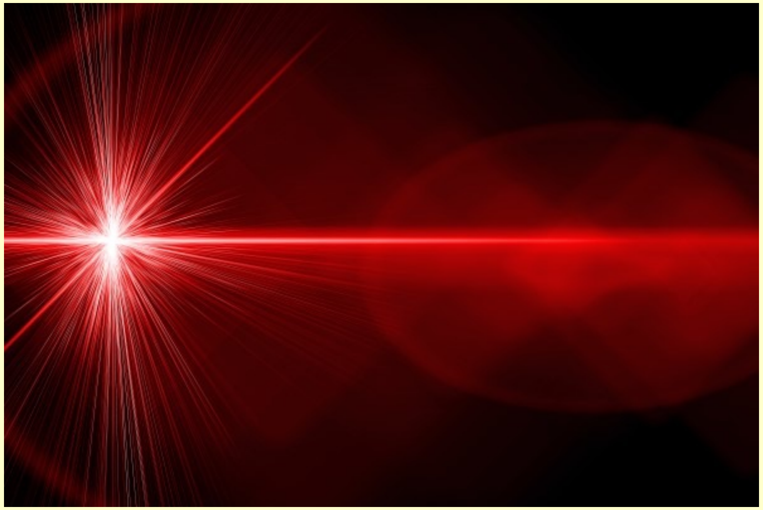
intensity grating



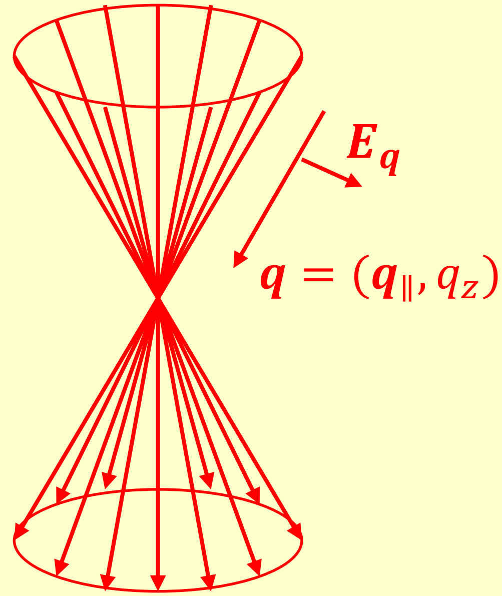
polarization grating

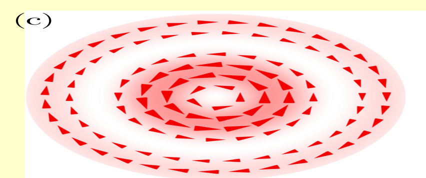
Particle/energy/spin diffusion, Long-lived spin textures, Four-wave mixing

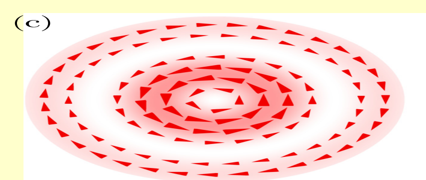
OPTICAL BEAMS



Bessel beams







Superposition of plane waves

$$\boldsymbol{E}(\boldsymbol{r},t) = \sum_{\boldsymbol{q}} \boldsymbol{E}_{\boldsymbol{q}} \exp(i\boldsymbol{q}\cdot\boldsymbol{r} - i\omega t) + \text{c.c.}$$

$$|\boldsymbol{q}| = \omega/c$$

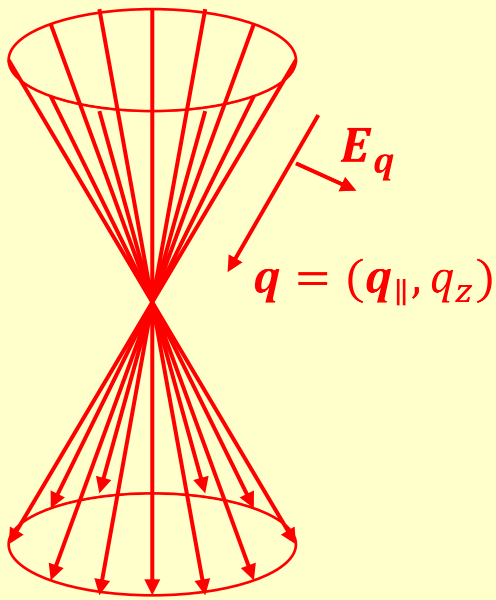
Paraxial approximation

$$|q_x|, |q_y| \ll q_z$$

Examples are Gaussian, Hermite-Gaussian, or Laguerre-Gaussian beams

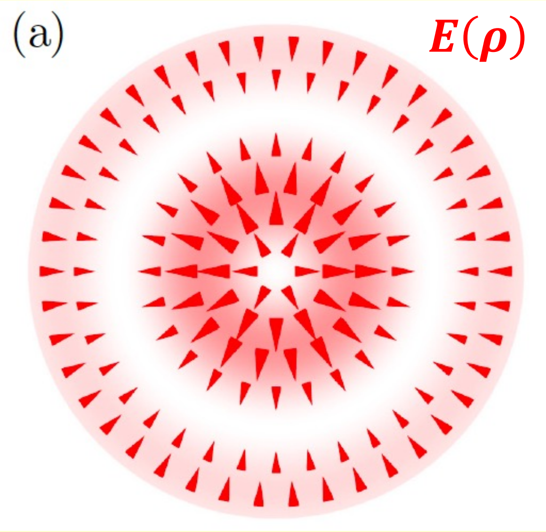
VECTOR BEAMS

Bessel beams

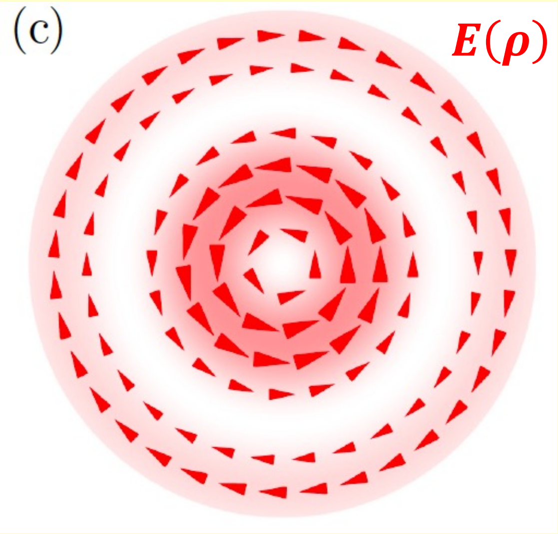


Electric field

(a) Radial beam



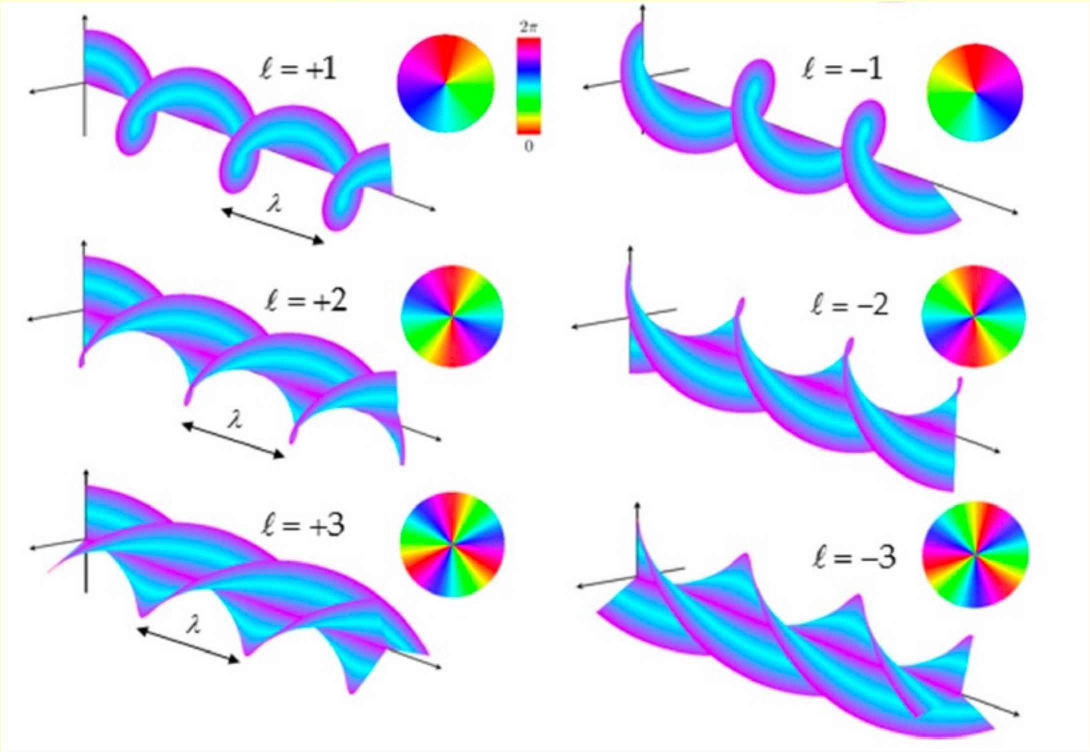
(c) Azimuthal beam



Distribution of electric field ***E*** in the beam cross-section

$$\boldsymbol{E}(\boldsymbol{\rho}, z) = \sum_{\boldsymbol{q}_{\parallel}} \boldsymbol{E}_{\boldsymbol{q}_{\parallel}} \exp(i q_z z + i \boldsymbol{q}_{\parallel} \cdot \boldsymbol{\rho})$$

TWISTED LIGHT



K.A. Forbes, D.L. Andrews, J. Phys. Photonics **3**, 022007 (2021)

Twisted light (optical vortices)

Electric field in the beam

$$\boldsymbol{E}(\boldsymbol{\rho}, z) \propto \exp(il\varphi)$$

l (integer) is the projection of orbital angular momentum (OAM)

Operator of OAM projection

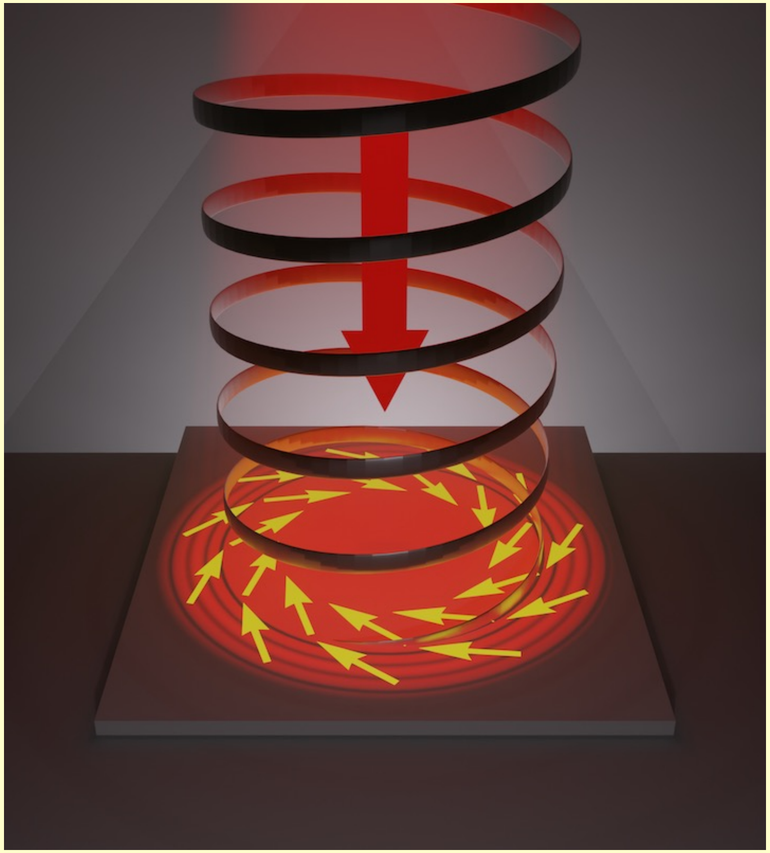
$$\hat{l}_z = -i\frac{\partial}{\partial\varphi}$$

Reviews: A. Forbes, M. de Oliveira, and M. R. Dennis, Structured light, Nat. Photonics **15**, 253 (2021)
B.A. Knyazev and V.G. Serbo, Phys. Usp. **61**, 449 (2018)

THz range: X. Wei, C. Liu, L. Niu et al., Appl. Opt. **54**, 10641 (2015)
Y.Y. Choporova, B.A. Knyazev, G.N. Kulipanov et al., Phys. Rev. A **96**, 023846 (2017)

Variety of applications in microscopy, imaging, metrology, quantum information, etc.

RESPONSE OF 2D SYSTEMS TO STRUCTURED RADIATION



Electric field of incident radiation in the 2D electron gas plane

$$\boldsymbol{E}(\boldsymbol{r},t) = \boldsymbol{E}(\boldsymbol{r})\exp(-i\omega t) + \mathrm{c.c.}$$

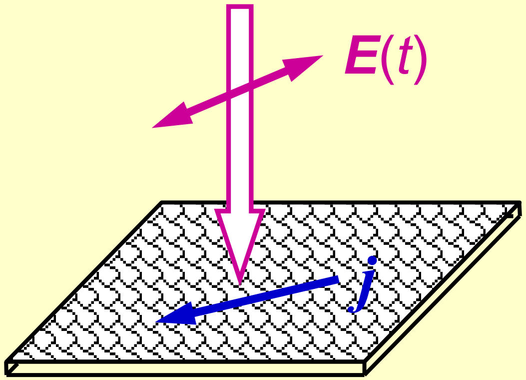
↑

(complex) amplitude
varying in 2D plane

⇩

charge/spin/valley currents $\boldsymbol{j}(\boldsymbol{r})$

RESPONSE TO ELECTROMAGNETIC FIELD



Electric field of incident plane wave

$$\boldsymbol{E}(\boldsymbol{r},t) = \boldsymbol{E}(\boldsymbol{r})\exp(-i\omega t) + \text{c.c.}$$

↑ (complex) amplitude

Electric current

Second-order effects

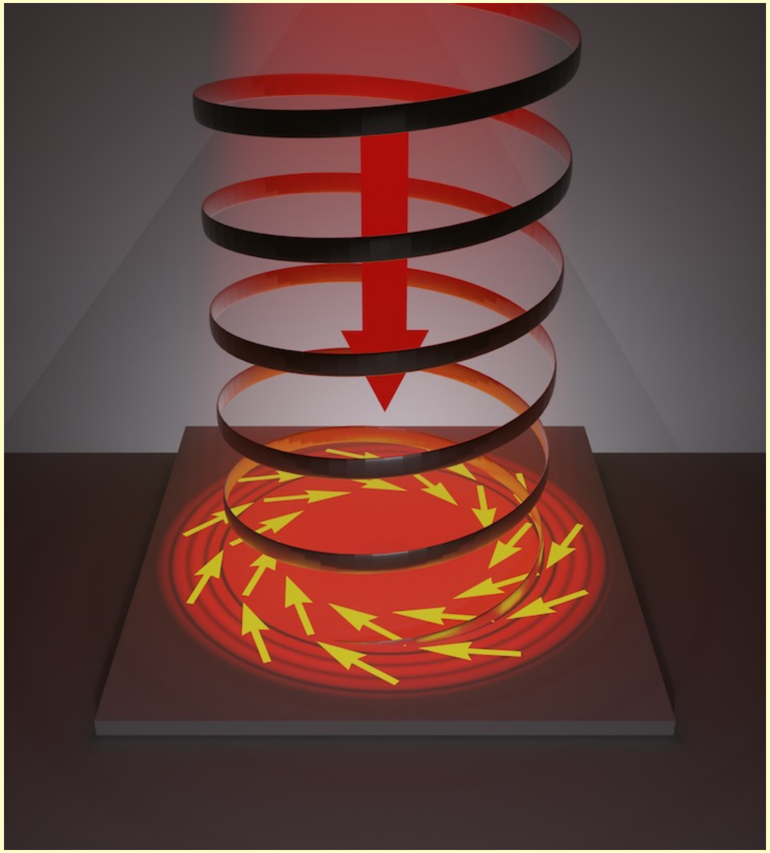
$$j_\alpha = \sum_\beta \sigma_{\alpha\beta} E_\beta + \sum_{\beta\gamma} P_{\alpha\beta\gamma} E_\beta E_\gamma^* + \sum_{\beta\gamma} D_{\alpha\beta\gamma} E_\beta E_\gamma + \ldots$$

dc current   current at 2ω

Mechanisms of second-order effects induced by homogeneous radiation

- Macroscopic inhomogeneity (*p*-*n* junction, asymmetry of contacts, ratchets)
- Lack of space inversion symmetry at microscopic level (Photogalvanic effects: G.E. Pikus, E.L. Ivchenko, V.I. Belinicher, B.I. Sturman, M.V. Entin, L.I. Magarill et al.)
- Photon drag (light pressure), in-plane dc current

SECOND-ORDER RESPONSE



Electric field of incident radiation in the 2D electron gas plane

$$\boldsymbol{E}(\boldsymbol{r},t) = \boldsymbol{E}(\boldsymbol{r})\exp(-i\omega t) + \mathrm{c.c.}$$

↑

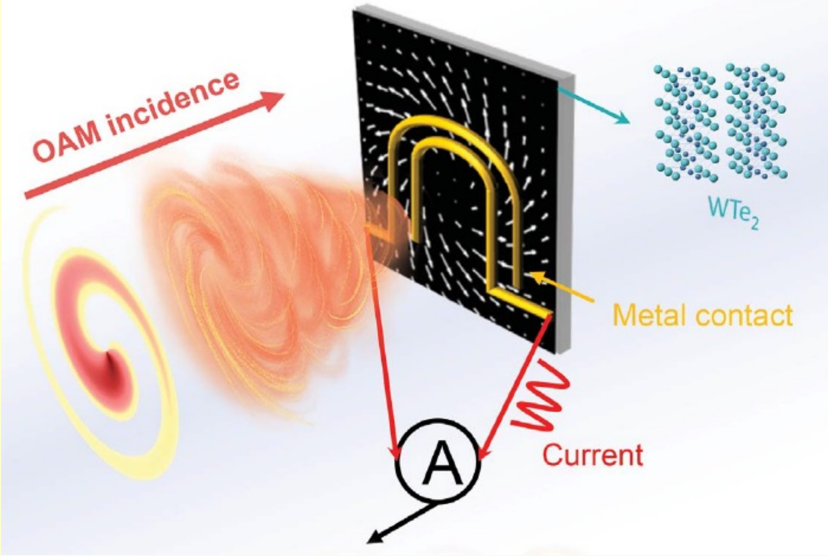
(complex) amplitude varying in 2D plane

⇩

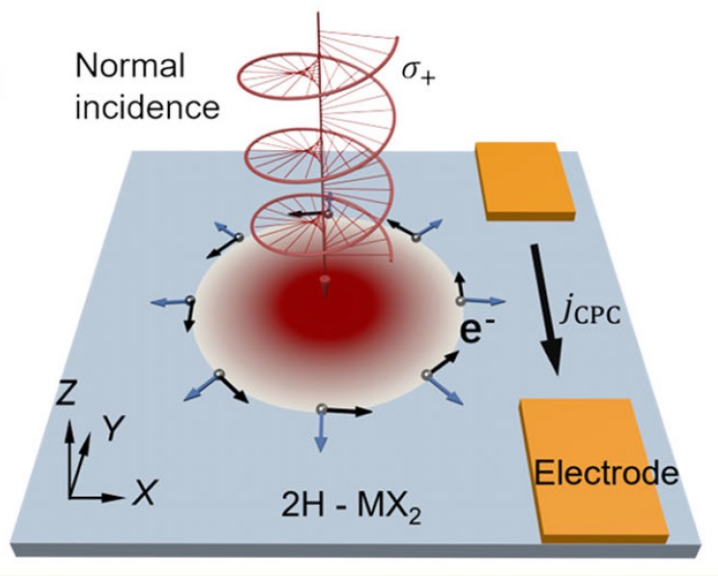
dc currents $j_\alpha^{(0)}(\boldsymbol{r}) \propto E_\beta \frac{\partial}{\partial r_\gamma} E_\delta^*$

currents at 2ω $j_\alpha^{(2\omega)}(\boldsymbol{r}) \propto E_\beta \frac{\partial}{\partial r_\gamma} E_\delta$

PHOTORESPONSE TO STRUCTURED RADIATION: SELECTED EXPERIMENTS



Z. Ji, W. Liu, S. Krylyuk et al., Science **368**, 763 (2020)
S. Sederberg et al., Nat. Photon. **14**, 680 (2020)



K. Wang et al., Nat. Comm. **15**, 9036 (2024)

Inverse spin Hall effect of polarized electrons:
N.S. Averkiev, M.I. Dyakonov, Semicond. **17**, 393 (1983)
A.A. Bakun et al., JETP Lett. **40**, 1293 (1984)

Edge photocurrents:
J. Karch et al., PRL **107**, 276601 (2011)
S. Candussio et al., PRB **102**, 045406 (2020)

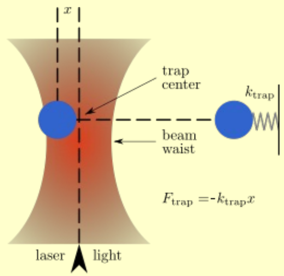
RELATED PHENOMENA

Ponderomotive forces, e.g., in plasma

V. B. Krapchev, Kinetic theory of the ponderomotive effects in a plasma, Phys. Rev. Lett. (1979)

Optical trapping of atoms, molecules, nanoparticles, etc.

A. Ashkin, Acceleration and trapping of particles by radiation pressure, Phys. Rev. Lett. (1970)

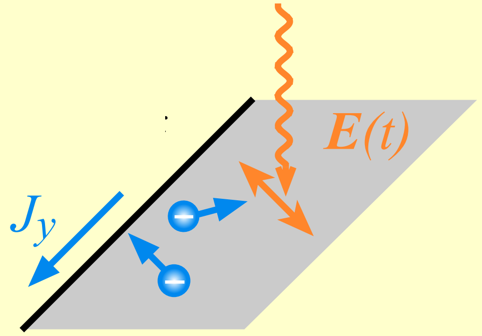


Surface currents and second harmonic generation in metals

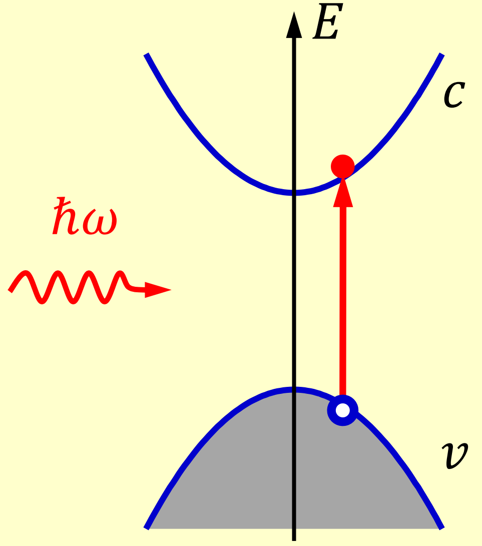
S.S. Jha, Theory of optical harmonic generation at a metal surface, Phys. Rev. (1965)
J. Rudnick and E.A. Stern, Second-harmonic radiation from metal surfaces, Phys. Rev. B (1971)
V.I. Perel' and Ya. M. Pinskii, Constant current in conducting media …, Phys. Solid State (1973)
V.L. Gurevich, R. Laiho, Photomagnetism of metals: Photoinduced surface current, Phys. Rev. B (1993)

Edge photogalvanic effects and second harmonic generation in 2D systems

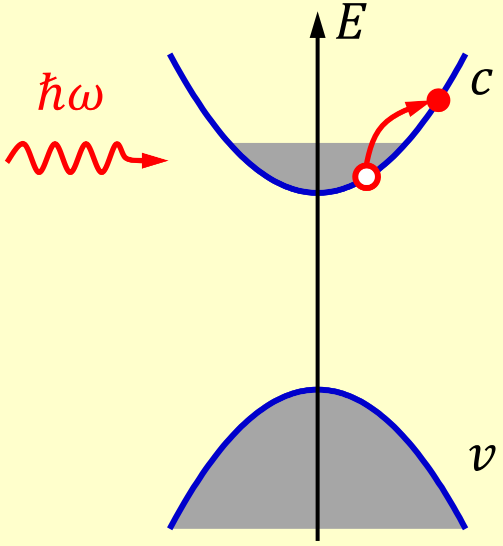
J. Karch et al., Terahertz radiation driven chiral edge currents in graphene, Phys. Rev. Lett. (2011)
S. Candussio et al., Edge photocurrent driven by terahertz electric field in bilayer graphene, Phys. Rev. B (2020)
M.V. Durnev and S.A.T., Phys. Rev. B (2021, 2022), Appl. Sci. (2023)



INTER-BAND AND INTRA-BAND OPTICAL TRANSITIONS



Direct inter-band
optical transitions



Indirect intra-band
optical transitions

OUTLINE

- Introduction. Structured light
- Intra-band response to structured electromagnetic field
  - Kinetic theory
  - Three contributions to photocurrent
  - Second harmonic generation due to radiation structure
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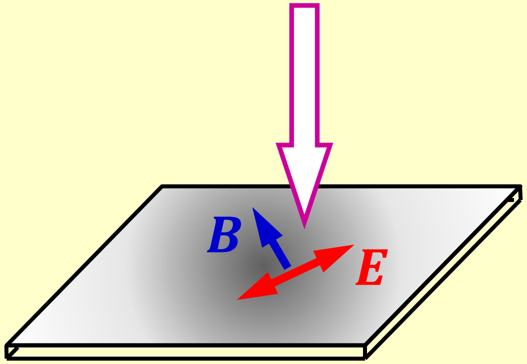
QUASI-CLASSICAL APPROACH

Boltzmann equation for electron distribution function $f(\boldsymbol{p},\boldsymbol{r},t)$

$$\frac{\partial f}{\partial t}+\boldsymbol{v}\cdot\frac{\partial f}{\partial \boldsymbol{r}}+e\left[\boldsymbol{E}_{\parallel}(\boldsymbol{r},t)+\frac{1}{c}\,\boldsymbol{v}\times\boldsymbol{B}_z(\boldsymbol{r},t)\right]\cdot\frac{\partial f}{\partial \boldsymbol{p}}=\mathrm{I}\,\{f\}$$



Electric $\boldsymbol{E}(\boldsymbol{r},t)$ and magnetic $\boldsymbol{B}(\boldsymbol{r},t)$ fields of radiation

$$B_z=-i\,\frac{c}{\omega}\left(\frac{\partial E_y}{\partial x}-\frac{\partial E_x}{\partial y}\right)$$

Collision integral (relaxation time approximation)

$$\mathrm{I}\,\{f\}=\frac{f-\langle f\rangle}{\tau}+\mathrm{I}_{e-e}\{f\}+\mathrm{I}_{\varepsilon}\{f\}$$

Solution to second order in the electric field, i.e., the radiation intensity

Assumptions: length of field variation $L(\sim\lambda)\gg l$ mean free path,
spatial dispersion of screening is negligible at $L\gg(2\pi\sigma/c)\lambda$

CONTRIBUTIONS TO PHOTOCURRENT

Photocurrent density $$\boldsymbol{j} = \boldsymbol{j}^{(\mathrm{th})} + \boldsymbol{j}^{(\mathrm{pol})} + \boldsymbol{j}^{(\mathrm{ph})}$$

(i) Photothermoelectric current

$$\boldsymbol{j}^{(\mathrm{th})} = -2\frac{e\tau\tau_\varepsilon \,\mathrm{Re}\,\sigma}{m^*}\nabla S_0$$

(ii) Currents by polarization gradients

$$j_x^{(\mathrm{pol})} = -\frac{e\tau^2 \,\mathrm{Re}\,\sigma}{m^*}\left(\frac{\partial S_1}{\partial x} + \frac{\partial S_2}{\partial y} - \frac{1}{\omega\tau}\frac{\partial S_3}{\partial y}\right)$$

$$j_y^{(\mathrm{pol})} = -\frac{e\tau^2 \,\mathrm{Re}\,\sigma}{m^*}\left(\frac{\partial S_2}{\partial x} - \frac{\partial S_1}{\partial y} + \frac{1}{\omega\tau}\frac{\partial S_3}{\partial x}\right)$$

(ii) Currents by phase gradient

$$\boldsymbol{j}^{(\mathrm{ph})} = -2\frac{e\tau \,\mathrm{Re}\,\sigma}{m^*\omega}\mathrm{Im}(E_x\nabla E_x^* + E_y\nabla E_y^*)$$

"Stokes" parameters

$S_0 = \left|E_\parallel\right|^2$ intensity

$S_1 = |E_x|^2 - \left|E_y\right|^2$

$S_2 = (E_xE_y^* + E_yE_x^*)$

$S_3 = i\left(E_xE_y^* - E_yE_x^*\right)$
$\propto P_{circ}$

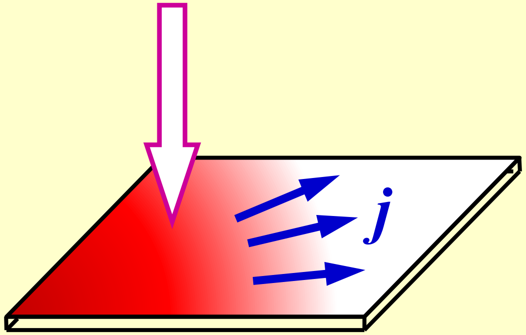
σ the high-frequency conductivity

A.A. Gunyaga, M.V. Durnev, and S.A.T., Phys. Rev. B **108**, 115402 (2023)

(I) PHOTOTHERMOELECTRIC CURRENT

Photothermoelectric current

$$\boldsymbol{j}^{(\mathrm{th})} = -2\frac{e\tau\tau_\varepsilon \operatorname{Re}\sigma}{m^*}\nabla S_0$$



Stokes parameter

$S_0 = \left|\boldsymbol{E}_\parallel\right|^2$ intensity

High-frequency conductivity

$$\operatorname{Re}\sigma = \frac{ne^2\tau/m^*}{1+(\omega\tau)^2}$$

Momentum and energy relaxation times

τ and τ_ε

(II) CURRENTS DRIVEN BY POLARIZATION GRADIENTS

Currents by polarization gradients

$$j_x^{(\mathrm{pol})} = -\frac{e\tau^2\,\mathrm{Re}\,\sigma}{m^*}\left(\frac{\partial S_1}{\partial x} + \frac{\partial S_2}{\partial y} - \frac{1}{\omega\tau}\frac{\partial S_3}{\partial y}\right)$$

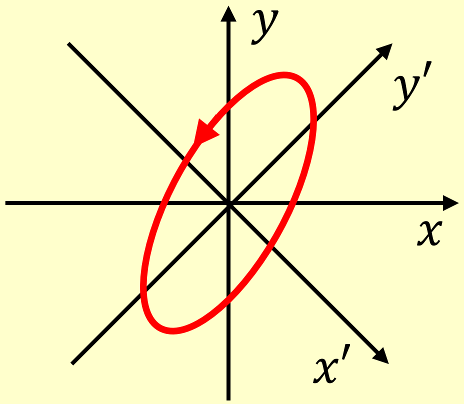
$$j_y^{(\mathrm{pol})} = -\frac{e\tau^2\,\mathrm{Re}\,\sigma}{m^*}\left(\frac{\partial S_2}{\partial x} - \frac{\partial S_1}{\partial y} + \frac{1}{\omega\tau}\frac{\partial S_3}{\partial x}\right)$$

Polarization Stokes parameters

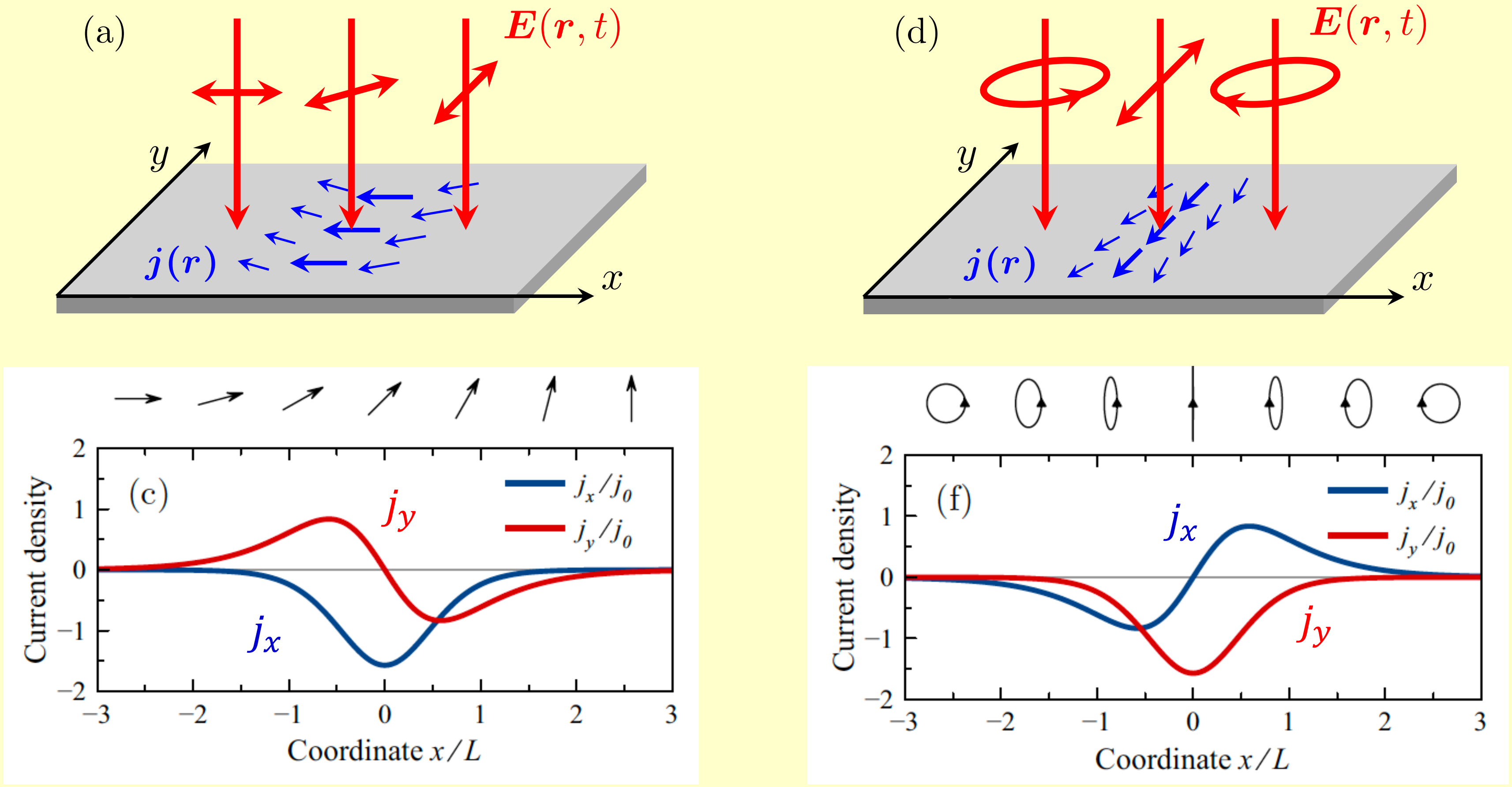
$$S_1 = |E_x|^2 - |E_y|^2 \propto P_{\mathrm{lin}}$$

$$S_2 = \left(E_x E_y^* + E_y E_x^*\right) \propto P_{\mathrm{diag}}$$

$$S_3 = i\left(E_x E_y^* - E_y E_x^*\right) \propto P_{\mathrm{circ}}$$



PHOTOCURRENTS BY POLARIZATION GRADIENTS



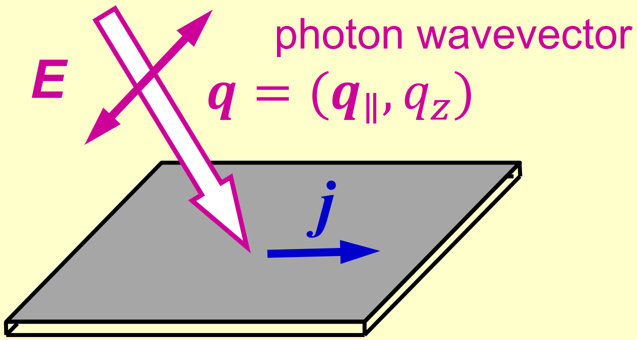
(II) CURRENTS DRIVEN BY PHASE GRADIENT

Currents by the gradient of the phase

$$\boldsymbol{j}^{(\mathrm{ph})} = -2\frac{e\tau\,\mathrm{Re}\,\sigma}{m^*\omega}\mathrm{Im}(E_x\nabla E_x^* + E_y\nabla E_y^*)$$

$$\propto S_0\,\boldsymbol{\nabla}\varphi(\boldsymbol{r})$$ for the field $\boldsymbol{E}(\boldsymbol{r}) = \boldsymbol{E_0}\exp[i\varphi(\boldsymbol{r})]$

Example: oblique incidence of plane wave



Phase in the 2DEG plane

$$\varphi = \boldsymbol{q}_\parallel \cdot \mathbf{r}$$

Photocurrent

$$\boldsymbol{j} \propto \boldsymbol{q}_\parallel |E|^2$$ photon drag

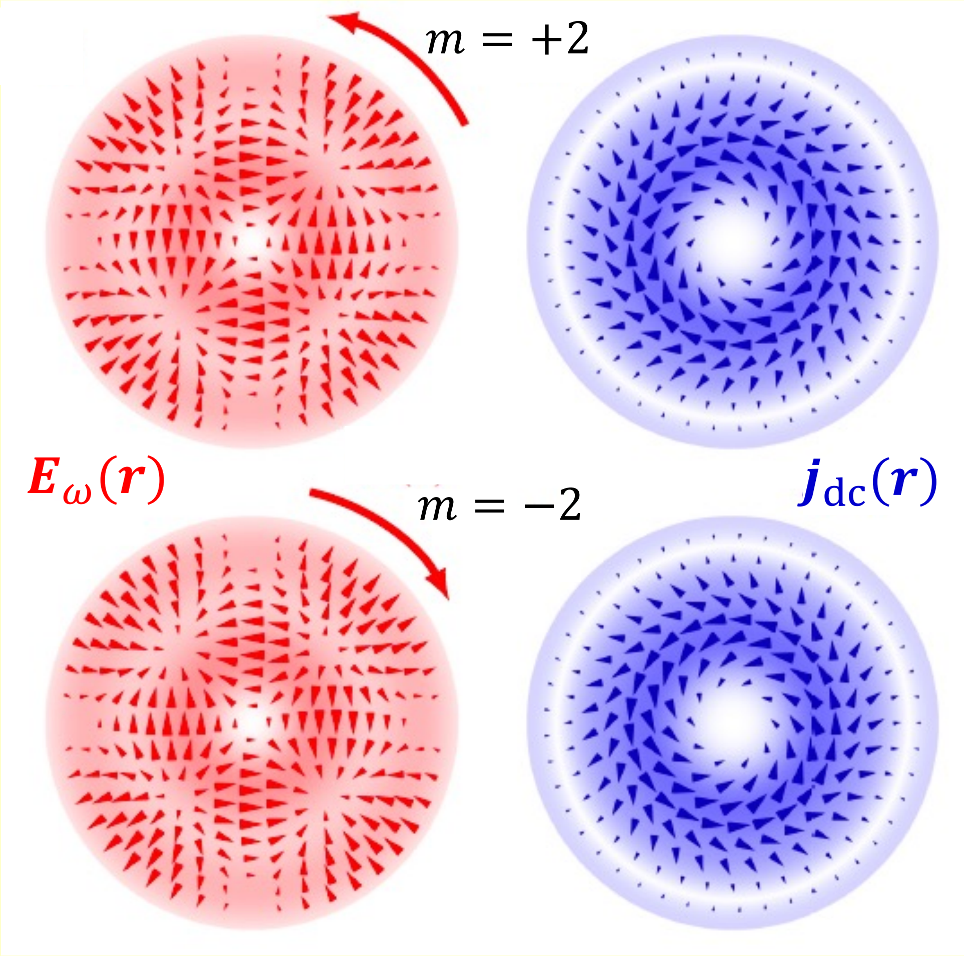
✓ Here,
generalized photon drag effect

Photon drag:

- A.M. Danishevskii et al., JETP (1970)
- A.F. Gibson et al., Appl. Phys. Lett. (1970)
- V.I. Perel’, Ya.M. Pinskii, Phys. Solid State (1973)
- J. Karch et al., Phys. Rev. Lett. (2010)
- M.V. Entin, L.I. Magarill et al., Phys. Rev. B (2010)
- P. A. Obraztsov et al., Phys. Rev. B (2014)

PHOTOCURRENTS BY BESSEL BEAMS

AC E-fields and DC currents for radial Bessel beams with $m = \pm 2$



Radial and azimuthal components of the photocurrent are controlled by the beam polarization and orbital angular momentum

$$j_r^{(th)} = j_0 \frac{\tau_\varepsilon}{\tau} \{J_{m+1}(J_m - J_{m+2}) - J_{m-1}(J_m - J_{m-2}) - [J_{m+1}(J_m - J_{m+2}) + J_{m-1}(J_m - J_{m-2})]\, p_3\}$$

$$j_r^{(pol)} + j_r^{(ph)} = j_0 J_m (J_{m+1} - J_{m-1})\, p_1,$$

$$j_\varphi^{(pol)} + j_\varphi^{(ph)} = j_0 J_m (J_{m+1} - J_{m-1}) \left(p_2 + \frac{p_3}{\omega\tau} \right) - \frac{j_0}{\omega\tau} J_m (J_{m+1} + J_{m-1}),$$

$$j_0 = - \frac{n e^3 \tau^3 E_0^2 q_\parallel}{m^{*2}(1 + \omega^2 \tau^2)}$$

A.A. Gunyaga, M.V. Durnev, and S.A.T., Phys. Rev. B **108**, 115402 (2023)

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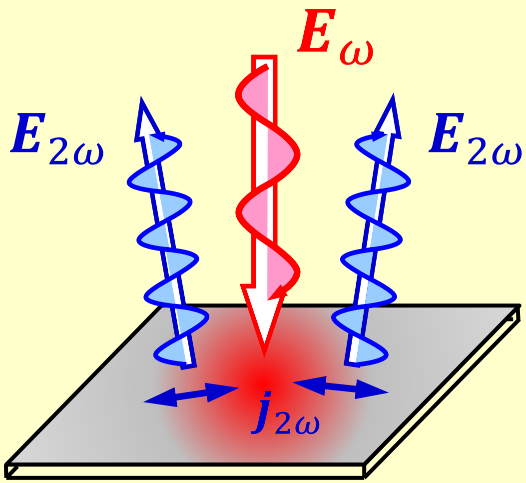
SECOND HARMONIC DUE TO RADIATION STRUCTURE



Isotropic centrosymmetric 2D medium, but structured (inhomogeneous) radiation

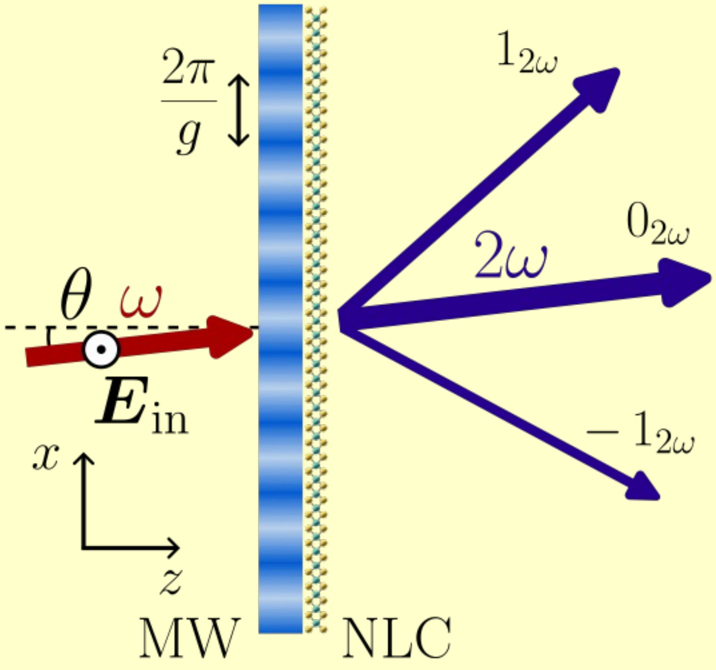
Electric current at double frequency

$$j_{2\omega} = \frac{-ie\sigma_0\tau}{m^*\omega(1-i\omega\tau)(1-2i\omega\tau)^2}\Big[(1-i\omega\tau)\nabla(\boldsymbol{E}_\parallel\cdot\boldsymbol{E}_\parallel) - (\boldsymbol{E}_\parallel\cdot\nabla)\boldsymbol{E}_\parallel + (1+4i\omega\tau)\,\boldsymbol{E}_\parallel\,(\nabla\cdot\boldsymbol{E}_\parallel)\Big]$$

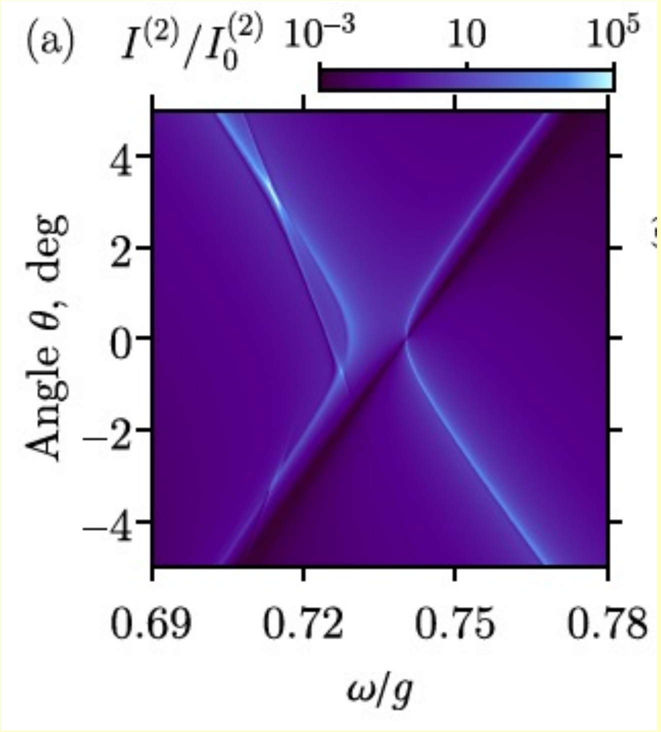
A.A. Gunyaga, M.V. Durnev, and S.A.T., Phys. Rev. Lett. **134**, 156901 (2025)

See also
Surface SHG: N. Bloembergen et al., Phys. Rev. (1968); J.E. Sipe et al., Phys. Rev. B (1980)
Edge SHG: M.V. Durnev and S.A.T., Phys. Rev. B (2022)

ENHANCEMENT OF SECOND HARMONIC GENERATION BY STRUCTURING THE NEAR FIELD



Intensity of second-harmonic diffraction beams



E.S. Vyatkin and S.A.T., ArXiv:2511.04325

N. Bernhardt, K. Koshelev, S.J. White et al., Nano Letters (2020)
T. Ning, L. Zhao, Y. Huo et al., Nanophotonics (2023)
H. Ling, Y. Tang, X. Tian et al., Nano Letters (2025)

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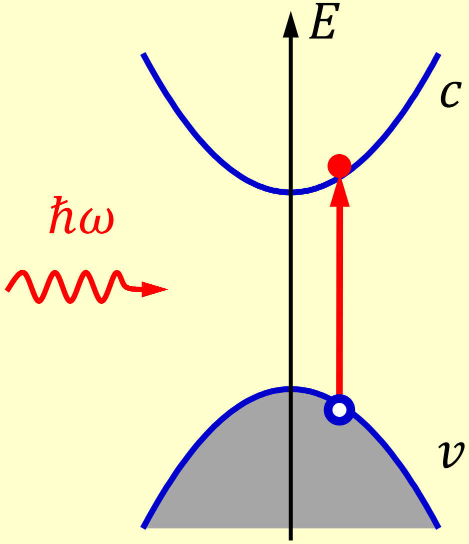
INTER-BAND OPTICAL TRANSITIONS



Incident field

$$\boldsymbol{A}(\boldsymbol{r},t) = \boldsymbol{A}(\boldsymbol{r})\exp(-i\omega t) + \mathrm{c.c.}$$

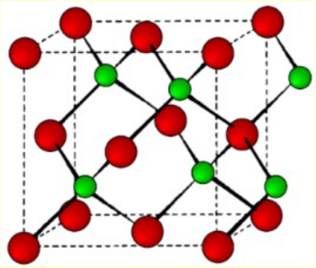
Standard approach

$$g(\boldsymbol{k}) = \frac{2\pi}{\hbar}|\boldsymbol{p}_{cv}\cdot\boldsymbol{A}|^2\delta(E_c - E_v - \hbar\omega)$$

information about the field phase is lost

QUANTUM MECHANICAL DESCRIPTION

Crystal lattice



Bloch states in Brillouin zone

$$\psi_{n\mathbf{k}} = \exp(i\mathbf{k}\cdot\mathbf{r})\,u_{n\mathbf{k}}(\mathbf{r})$$

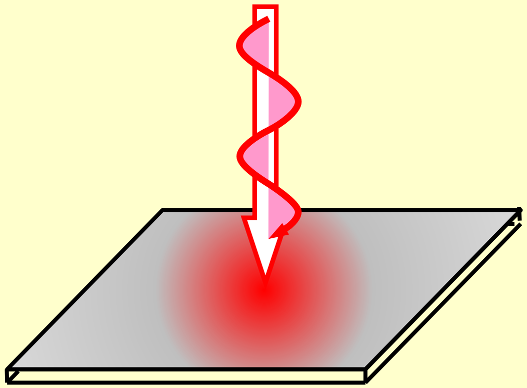
Description in terms of the density matrix $\rho_{n\boldsymbol{k},n'\boldsymbol{k}'}$

Density matrix of conduction-band electrons $\rho_{\boldsymbol{k}\boldsymbol{k}'} = \rho_{c\boldsymbol{k},c\boldsymbol{k}'}$

Quasi-classical distribution function by Wigner transformation

$$f(\boldsymbol{k},\boldsymbol{r}) = \sum_{\boldsymbol{p}} \rho_{\boldsymbol{k}+\boldsymbol{p}/2,\,\boldsymbol{k}-\boldsymbol{p}/2} \exp(i\boldsymbol{p}\cdot\boldsymbol{r})$$

INTER-BAND TRANSITIONS BY STRUCTURED LIGHT



Incident field in the 2D plane

$$\boldsymbol{A}(\boldsymbol{r},t) = \sum_{\boldsymbol{q}} \boldsymbol{A}_{\boldsymbol{q}} \exp(i\boldsymbol{q}\cdot\boldsymbol{r} - i\omega t) + \mathrm{c.c.}$$

in-plane wave vector

Density matrix generation

$$g_{\boldsymbol{k}\boldsymbol{k}'} = \frac{\pi}{\hbar}\sum_{\boldsymbol{k}''} M_{c\boldsymbol{k},v\boldsymbol{k}''} M^*_{c\boldsymbol{k}',v\boldsymbol{k}''} [\delta(\varepsilon^c_{\boldsymbol{k}} - \varepsilon^v_{\boldsymbol{k}''} - \hbar\omega) + \delta(\varepsilon^c_{\boldsymbol{k}'} - \varepsilon^v_{\boldsymbol{k}''} - \hbar\omega)]$$

similar to spin density matrix
S.D. Ganichev, E.L. Ivchenko, S.A.T. et al., PRB 2003
V.A. Gorelov, S.A.T., and N. S. Averkiev, JETP 2011

Quasi-classical generation term by Wigner transformation

$$g(\boldsymbol{k},\boldsymbol{r}) = \sum_{\boldsymbol{p}} g_{\boldsymbol{k}+\boldsymbol{p}/2,\,\boldsymbol{k}-\boldsymbol{p}/2} \exp(i\boldsymbol{p}\cdot\boldsymbol{r})$$

QUASI-CLASSICAL GENERATION TERM

Optical generation rate

$$g(\boldsymbol{k},\boldsymbol{r}) = g^{(0)}(\boldsymbol{k},\boldsymbol{r}) + g^{(1)}(\boldsymbol{k},\boldsymbol{r}) + \ldots$$

expansion in the series of q/k

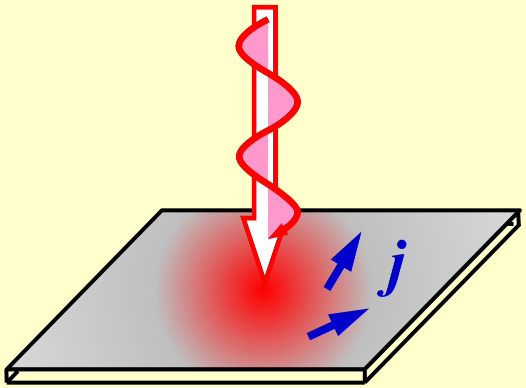
Zeroth order: Local field approximation

$$g^{(0)}(\boldsymbol{k},\boldsymbol{r}) = \frac{2\pi e^2}{\hbar c^2} |\boldsymbol{v}_{cv}(\boldsymbol{k}) \cdot \boldsymbol{A}(\boldsymbol{r})|^2 \delta(\varepsilon^c_{\boldsymbol{k}} - \varepsilon^v_{\boldsymbol{k}} - \hbar\omega)$$

First-order correction: Non-local corrections

$$\begin{aligned} g^{(1)}(\boldsymbol{k},\boldsymbol{r}) = {} & \frac{2\pi e^2}{\hbar c^2} \delta(\varepsilon^g_{\boldsymbol{k}} - \hbar\omega) \,\mathrm{Im}\left\{ [\boldsymbol{v}_{cv}(\boldsymbol{k}) \cdot \boldsymbol{A}(\boldsymbol{r})]^* [(\partial_{\boldsymbol{k}} - \partial_{\boldsymbol{k}'}) \cdot \nabla][\boldsymbol{v}_{cv}(\boldsymbol{k},\boldsymbol{k}') \cdot \boldsymbol{A}(\boldsymbol{r})] \right\} \\ & - \frac{2\pi e^2}{\hbar c^2} \delta(\varepsilon^g_{\boldsymbol{k}} - \hbar\omega) \,\mathrm{Im}\left\{ \partial_{\boldsymbol{k}} \left[\boldsymbol{v}_{cv}(\boldsymbol{k}) \cdot \boldsymbol{A}(\boldsymbol{r})\right]^* \cdot \nabla \left[\boldsymbol{v}_{cv}(\boldsymbol{k}) \cdot \boldsymbol{A}(\boldsymbol{r})\right] \right\} \\ & + \frac{2\pi e^2}{c^2} \delta'(\varepsilon^g_{\boldsymbol{k}} - \hbar\omega) \,\mathrm{Im}\left\{ [\boldsymbol{v}_{cv}(\boldsymbol{k}) \cdot \boldsymbol{A}(\boldsymbol{r})]^* (\boldsymbol{v}^v_{\boldsymbol{k}} \cdot \nabla) \left[\boldsymbol{v}_{cv}(\boldsymbol{k}) \cdot \boldsymbol{A}(\boldsymbol{r})\right] \right\} \;, \end{aligned}$$

PHOTOCURRENT BY STRUCTURED LIGHT



Two contributions to photocurrent density

$$\boldsymbol{j}(\boldsymbol{r}) = \boldsymbol{j}^{(\mathrm{loc})}(\boldsymbol{r}) + \boldsymbol{j}^{(\mathrm{nl})}(\boldsymbol{r})$$

(i) From generation term in local approximation

$$\boldsymbol{j}^{(\mathrm{loc})}(\boldsymbol{r}) = \sum_{\boldsymbol{k}} \boldsymbol{v}_{\boldsymbol{k}}^{c}\, f(\boldsymbol{k},\boldsymbol{r})$$

$f(\boldsymbol{k},\boldsymbol{r})$ is found from Boltzmann equation

$$\frac{\partial f(\boldsymbol{k},\boldsymbol{r})}{\partial t} + \boldsymbol{v}_{\boldsymbol{k}}^{c}\cdot\nabla f(\boldsymbol{k},\boldsymbol{r}) = g^{(0)}(\boldsymbol{k},\boldsymbol{r}) + I\{f\}$$

(ii) From non-local correction to generation term

$$\boldsymbol{j}^{(\mathrm{nl})}(\boldsymbol{r}) = \sum_{\boldsymbol{k}} \tau_1 g^{(1)}(\boldsymbol{k},\boldsymbol{r})\boldsymbol{v}_{\boldsymbol{k}}^{c} + \frac{\mathrm{i}}{2}\sum_{\boldsymbol{k}}\sum_{\alpha=x,y} \tau_1 \nabla_\alpha g^{(0)}(\boldsymbol{k},\boldsymbol{r})\left[(\partial_{k_\alpha} - \partial_{k'_\alpha})\boldsymbol{v}_{\boldsymbol{k},\boldsymbol{k}'}^{c}\right]_{\boldsymbol{k}'=\boldsymbol{k}}$$

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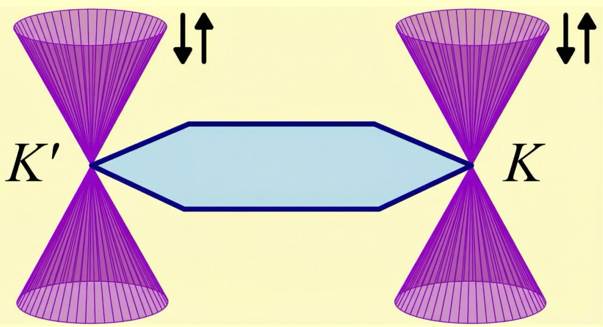
2D DIRAC MATERIALS

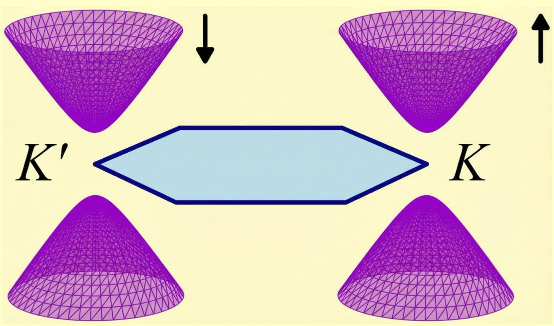
Hamiltonians in the valleys

$$H = a(\pm\sigma_x k_x + \sigma_y k_y) + \delta\sigma_z = \begin{pmatrix} \delta & (\pm k_x - ik_y)a \\ (\pm k_x + ik_y)a & -\delta \end{pmatrix}$$



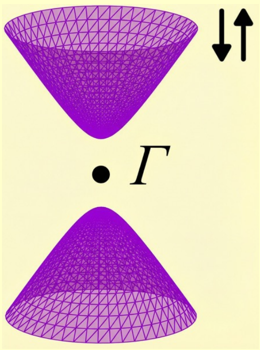
graphene

$\nu = \pm 1$ valleys



TMDC monolayers

$\nu = \pm 1$ spin/valleys

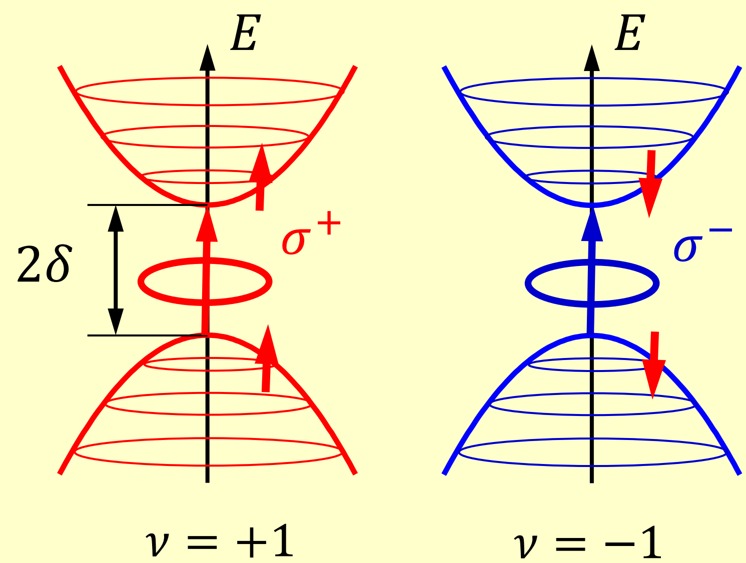


narrow-gap QWs
HgTe, InAs/GaSb

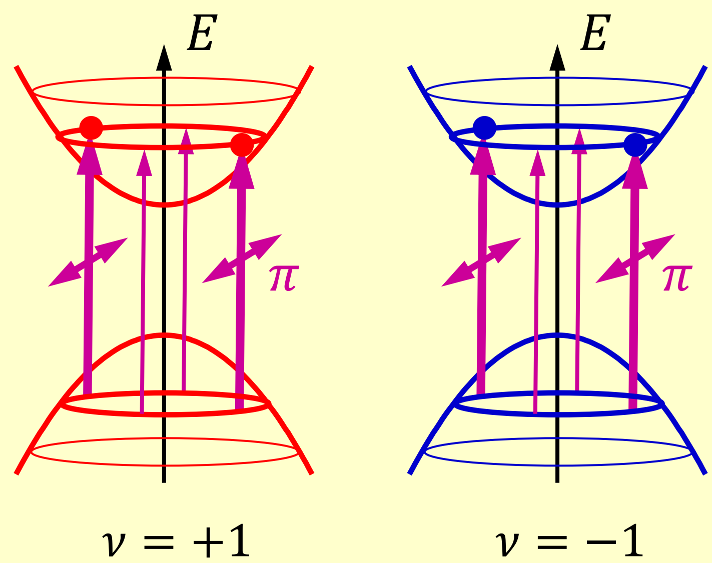
$\nu = \pm 1$ spin

2D DIRAC MATERIALS

Optical orientation of spin/valley
by circularly polarized light



Optical alignment of momenta
by linearly polarized light



Electric current $\boldsymbol{j}^e = e(\boldsymbol{j}_{+1} + \boldsymbol{j}_{-1})$

Valley/spin current $\boldsymbol{j}^s = \boldsymbol{j}_{+1} - \boldsymbol{j}_{-1}$

CONTRIBUTIONS TO ELECTRIC CURRENT

Electric current density

$$\boldsymbol{j} = \boldsymbol{j}^{(\mathrm{int})} + \boldsymbol{j}^{(\mathrm{pol})} + \boldsymbol{j}^{(\mathrm{ph})}$$

(i) Current by intensity gradient

$$\boldsymbol{j}^{(\mathrm{int})} = Q_1 \mathrm{Re}(E_x^* \boldsymbol{\nabla} E_x + E_x^* \boldsymbol{\nabla} E_x) \qquad \propto \boldsymbol{\nabla} S_0$$

(ii) Currents by polarization gradients

$$\boldsymbol{j}^{(\mathrm{pol})} = Q_2 \mathrm{Re}[\boldsymbol{E}^* (\boldsymbol{\nabla} \cdot \boldsymbol{E}) - \boldsymbol{E}^* \times (\boldsymbol{\nabla} \times \boldsymbol{E})] \qquad \propto \boldsymbol{\nabla} S_{1,2}$$

$$+ \; Q_3 \mathrm{Im}[\boldsymbol{E}^* (\boldsymbol{\nabla} \cdot \boldsymbol{E}) - (\boldsymbol{E} \cdot \boldsymbol{\nabla}) \boldsymbol{E}] \qquad \propto \boldsymbol{\nabla} S_3$$

(ii) Currents by phase gradient

$$\boldsymbol{j}^{(\mathrm{ph})} = Q_4 \, \mathrm{Im}(E_x^* \boldsymbol{\nabla} E_x + E_x^* \boldsymbol{\nabla} E_x)$$

$$+ \, Q_5 \, \mathrm{Im}[\boldsymbol{E}^* (\boldsymbol{\nabla} \cdot \boldsymbol{E}) - \boldsymbol{E}^* \times (\boldsymbol{\nabla} \times \boldsymbol{E})]$$

$$+ \, Q_6 \, \mathrm{Re}[\boldsymbol{E}^* (\boldsymbol{\nabla} \cdot \boldsymbol{E}) - (\boldsymbol{E} \cdot \boldsymbol{\nabla}) \boldsymbol{E}]$$

Similar equations for spin/valley current

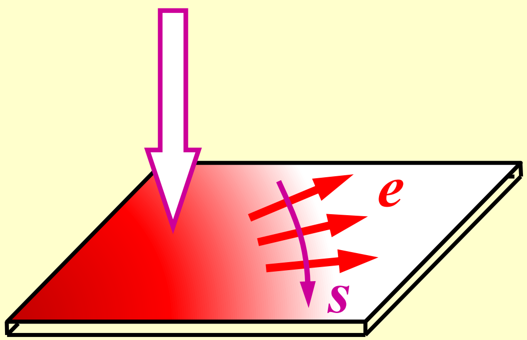
(I) CURRENTS BY INTENSITY GRADIENT

Electric current

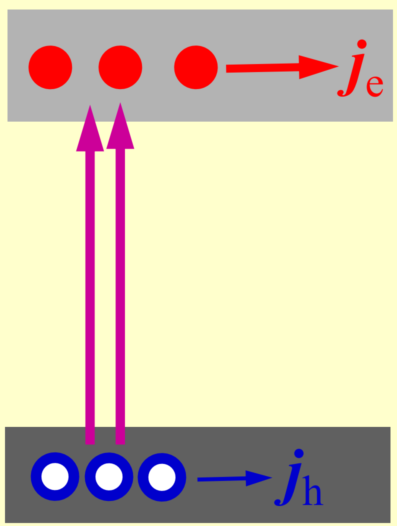
$$\boldsymbol{j}^{(\mathrm{int})} = 2Q_1 \mathrm{Re}(E_x^* \boldsymbol{\nabla} E_x + E_x^* \boldsymbol{\nabla} E_x) = Q_1 \boldsymbol{\nabla} S_0$$

intensity $S_0 = |\boldsymbol{E}_\parallel|^2$

Stokes parameter



Dember effect



For spin/valley currents: Dember effect + spin/valley Hall effect

(II) CURRENTS DRIVEN BY POLARIZATION GRADIENTS

Currents by polarization gradients

$$\boldsymbol{j}^{(\mathrm{pol})} = 2Q_2 \mathrm{Re}[\boldsymbol{E}^*(\boldsymbol{\nabla}\cdot\boldsymbol{E}) - \boldsymbol{E}^*\times(\boldsymbol{\nabla}\times\boldsymbol{E})] \quad \propto \boldsymbol{\nabla}\mathrm{S}_{1,2}$$

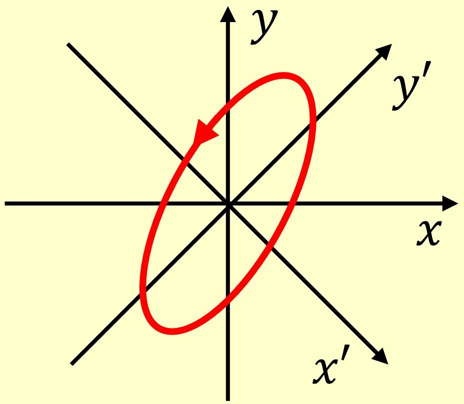
$$+ 2Q_3 \mathrm{Im}[\boldsymbol{E}^*(\boldsymbol{\nabla}\cdot\boldsymbol{E}) - (\boldsymbol{E}\cdot\boldsymbol{\nabla})\boldsymbol{E}] \quad \propto \boldsymbol{\nabla}\mathrm{S}_3$$

Polarization Stokes parameters

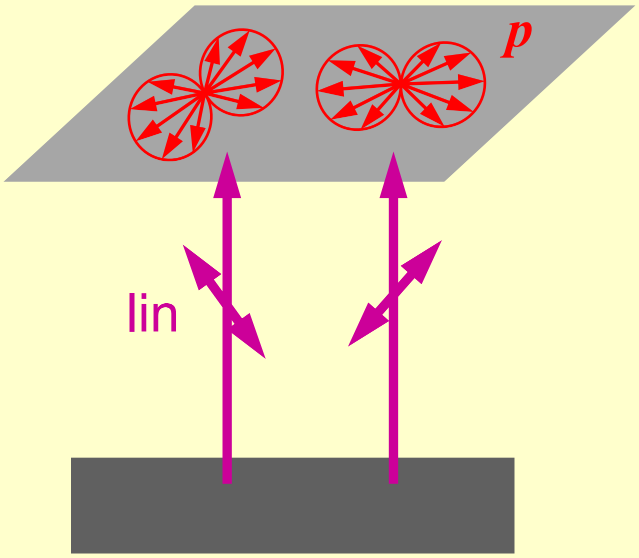
$$S_1 = |E_x|^2 - |E_y|^2 \propto P_{\mathrm{lin}}$$

$$S_2 = (E_x E_y^* + E_y E_x^*) \propto P_{\mathrm{diag}}$$

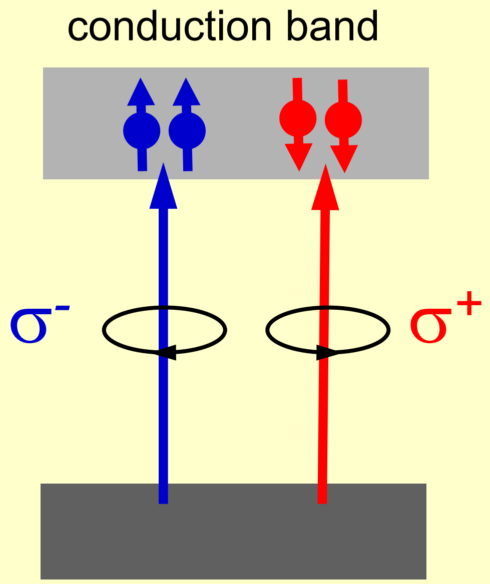
$$S_3 = i(E_x E_y^* - E_y E_x^*) \propto P_{\mathrm{circ}}$$



KEY PROCESSES CONTRIBUTING TO CURRENTS



Optical alignment
of electron momenta



Spin/valley selective
optical transitions

+ Conversion of currents due to spin/valley Hall effect and inverse spin/valley Hall effect

(III) CURRENTS DRIVEN BY PHASE GRADIENTS

Currents by the gradient of the phase

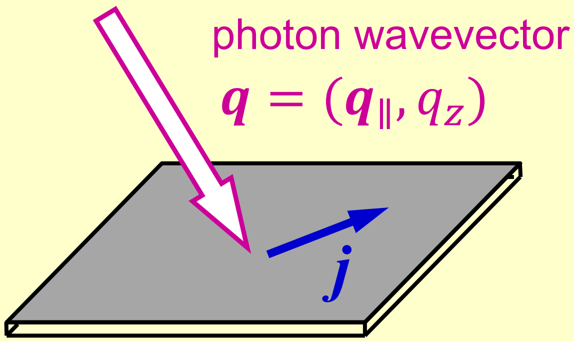
$$\boldsymbol{j}^{(\mathrm{ph})} = Q_4 \,\mathrm{Im}(E_x^* \boldsymbol{\nabla} E_x + E_x^* \boldsymbol{\nabla} E_x) \qquad \propto S_0 \boldsymbol{\nabla}\varphi$$

$$+ Q_5 \,\mathrm{Im}[\boldsymbol{E}^*(\boldsymbol{\nabla}\cdot\boldsymbol{E}) - \boldsymbol{E}^*\times(\boldsymbol{\nabla}\times\boldsymbol{E})] \qquad \propto S_{1,2} \boldsymbol{\nabla}\varphi$$

$$+ Q_6 \,\mathrm{Re}[\boldsymbol{E}^*(\boldsymbol{\nabla}\cdot\boldsymbol{E}) - (\boldsymbol{E}\cdot\boldsymbol{\nabla})\boldsymbol{E}] \qquad \propto S_3 \boldsymbol{\nabla}\varphi$$

for the field $\boldsymbol{E}(\boldsymbol{r}) = \boldsymbol{E_0} \exp[i\varphi(\boldsymbol{r})]$

Here, generalized photon drag and spin/valley photon drag effects



For plan wave

$$\varphi = \boldsymbol{q}_\parallel \cdot \mathbf{r}$$

Photocurrent

$$\boldsymbol{j} \propto \boldsymbol{q}_\parallel |E|^2 \quad \text{photon drag}$$

CHARGE AND SPIN-VALLEY CURRENTS. SUMMARY

	Electric currents	$\overset{\theta}{\leftrightarrows}$		Spin-valley currents	Realization
Q_1	$-\frac{\kappa e^3 L_e^2}{8\hbar\,\delta\, w^3}(w^2+1)$		W_1	$-\frac{\kappa e^2 \tau_1 a^2}{32\,\delta^2 w^5}(3w^2+1)$	$\propto \nabla S_0$
Q_2	$\frac{\kappa e^3 \tau_1 \tau_2 a^2}{32\hbar\,\delta\, w^5}(w^2-1)^2$		W_2	$\frac{\kappa e^2 \tau_1 a^2}{32\,\delta^2 w^5}(w^2-1)$	$\propto \nabla S_{1,2}$
Q_3	$\frac{\kappa e^3 \tau_1 a^2}{32\,\delta^2\, w^4}(w^2+3)$		W_3	$-\frac{\kappa e^2 L_{sv}^2}{4\hbar\,\delta\, w^2}$	$\propto \nabla S_3$
Q_4	$\frac{\kappa e^3 \tau_1 a^2}{32\,\delta^2\, w^6}[(w^2+1)^2+(w^4-1)(\ln\tau_1)']$		W_4	0	$\propto S_0 \nabla\varphi$
Q_5	$\frac{\kappa e^3 \tau_1 a^2}{64\,\delta^2\, w^6}(w^2-1)^2[1-(\ln\tau_1)']$		W_5	0	$\propto S_{1,2}\nabla\varphi$
Q_6	0		W_6	$-\frac{\kappa e^2 \tau_1 a^2}{16\,\delta^2 w^5}[(w^2+1)+(w^2-1)(\ln\tau_1)']$	$\propto S_3\nabla\varphi$

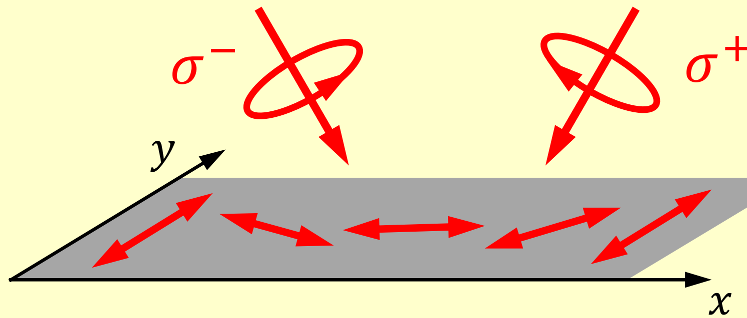
Parameters:

$w = \frac{\hbar\omega}{2\delta}$, 2δ the band gap

τ_1 and τ_2 the relaxation times, L_e and L_{sv} the electron and spin/valley diffusion lenghts

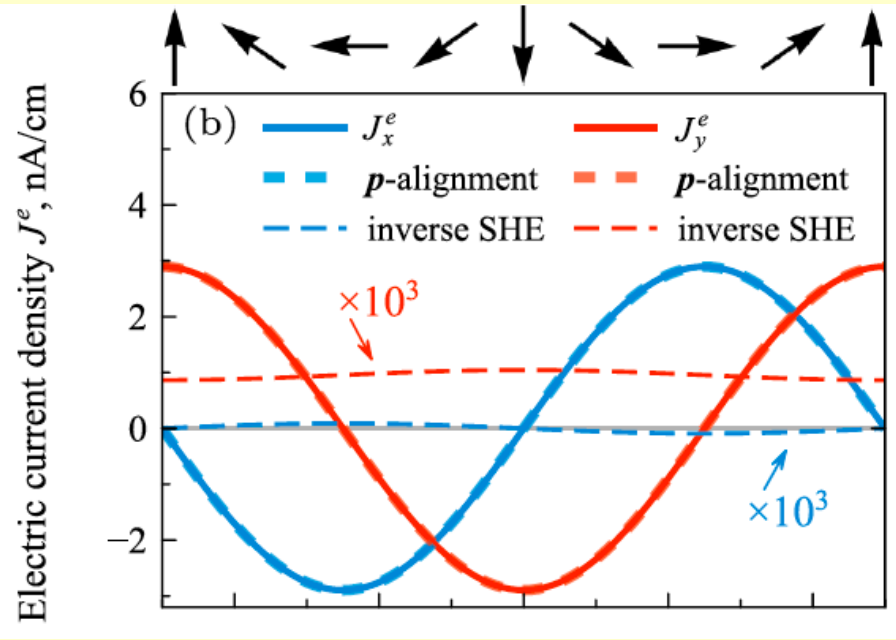
θ the valley Hall angle

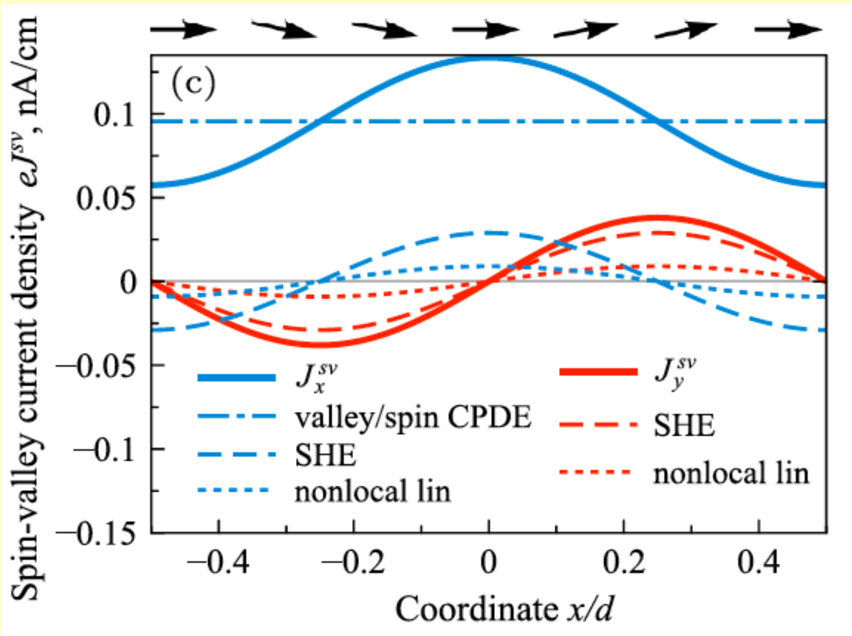
CURRENTS BY OPTICAL GRATING - I



Charge current

Valley/spin current





Relevant to TMDC, $\hbar\omega = 1.1E_g$, $q_x/q = 0.1, \tau = 1\text{ps}$, valley Hall angle $\theta = 0.01, I = 1\text{W/cm}^2$

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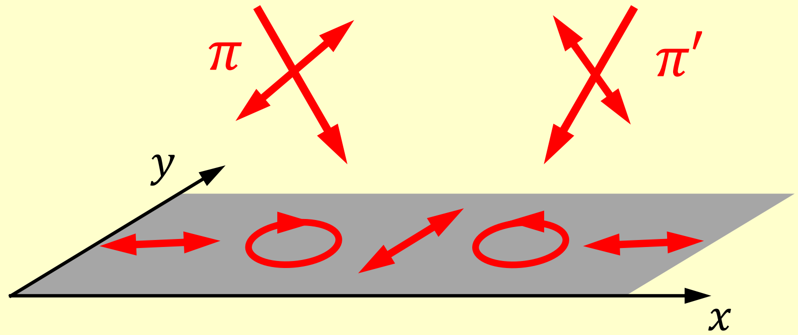
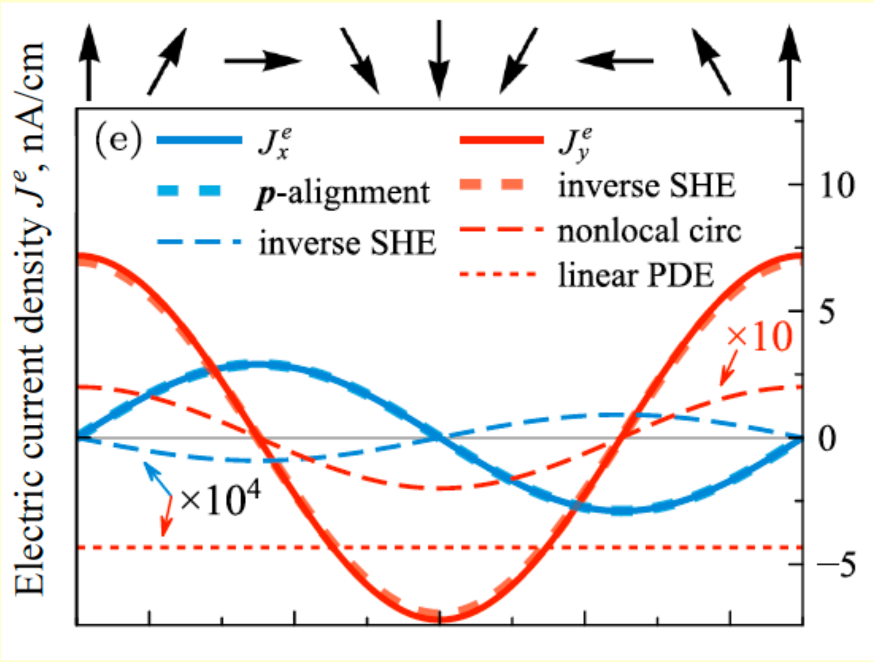
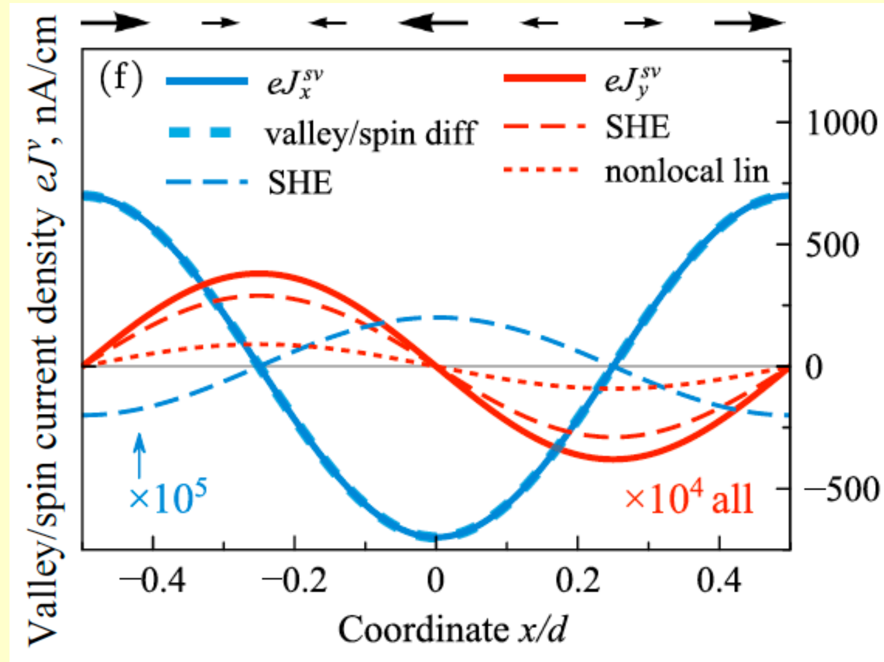
CURRENTS BY POLARIZATION GRATING - II



Charge current

Spin/valley current





Relevant to TMDC, $\hbar\omega = 1.1E_g\,, q_x/q = 0.1, \tau = 1\text{ps},\ \mathrm{L_{sv}} = 1\mu n, \theta = 0.01, I = 1\mathrm{W/cm}^2$

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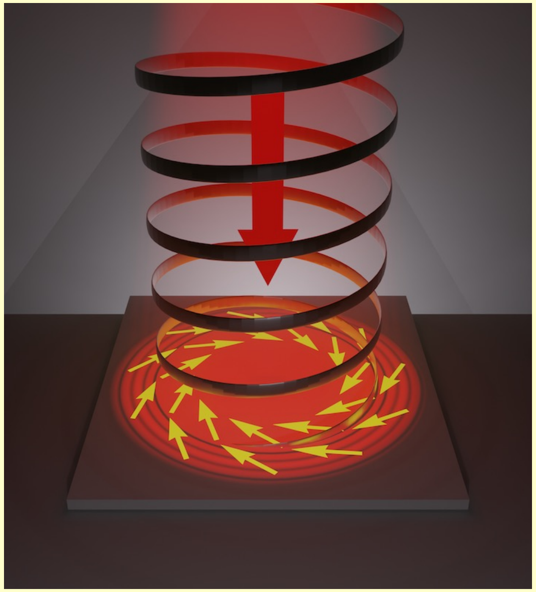
ФОТООТКЛИК ДВУМЕРНЫХ ПОЛУПРОВОДНИКОВ НА СТРУКТУРИРОВАННОЕ ИЗЛУЧЕНИЕ



- ✓ Постоянные токи, индуцированные структурированным излучением.
  Вклады, связанные с градиентами интенсивности, поляризации, фазы э/м волны.

- ✓ Генерация второй гармоники в 2D системах за счет пространственной структуры излучения

  Токи других квазичастиц: экситонов, вихрей, скирмионов, спиновые, долинные токи

- ✓ Структурированное излучение раздвигает границы фотоэлектрических явлений и нелинейной оптики за рамки ограничений, налагаемых симметрией кристаллической решетки