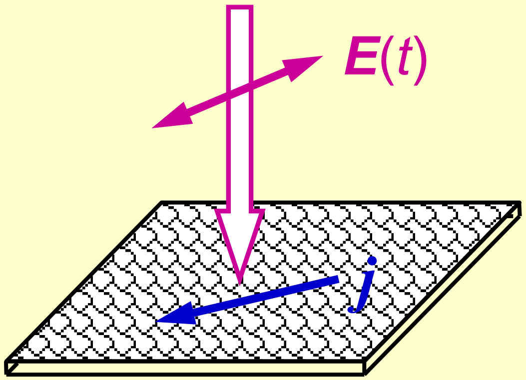
ФОТОГАЛЬВАНИЧЕСКИЕ ЭФФЕКТЫ
В НИЗКОРАЗМЕРНЫХ СИСТЕМАХ – 2
ГЕОМЕТРИЧЕСКИЕ ЭФФЕКТЫ

С.А. Тарасенко

ФТИ им. А.Ф. Иоффе, Санкт-Петербург

Летняя школа фонда Базис - 2024
«Современные проблемы физики конденсированного состояния»

PHOTOCURRENTS IN 2D SYSTEMS



Excitation by plane wave

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

↑ (complex) amplitude

Photocurrents

$$\boldsymbol{j} \propto EE^*, \text{i. e.}, \propto I$$

↑ radiation intensity

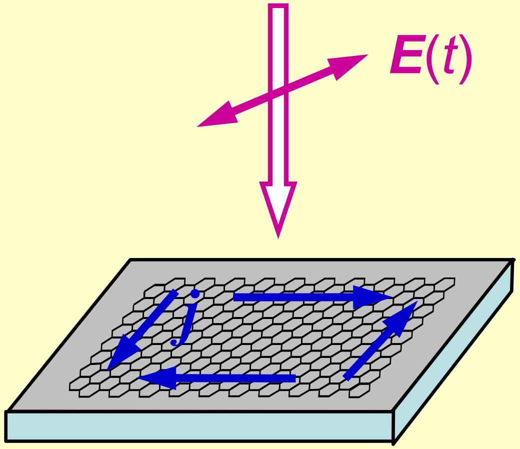
Mechanisms of dc current (photocurrent) induced by homogeneous radiation

- Macroscopic inhomogeneity (*p*-*n* junction, asymmetry of contacts, ratchets)
- Lack of space inversion symmetry at microscopic level (photogalvanic effects)
- Photon drag (light pressure)

ПЛАН ЛЕКЦИИ

- Краевые фотогальванические эффекты в 2D материалах
  - микроскопические механизмы, кинетическая теория
    эксперимент на графене
  - генерация второй гармоники
- Фототоки, индуцированные структурированным светом
- Основные результаты

EDGE CURRENTS IN TWO-DIMENSIONAL SYSTEMS



Symmetry is naturally broken at edges
⇒ Second-order effects get allowed

First study of edge photogalvanic effect
in 2D systems (graphene)

J. Karch et al., Phys. Rev. Lett. **107**, 276601 (2011)

Surface photogalvanic effects in bulk materials and films

L.I. Magarill, M.V. Entin, Phys. Solid State (1979), JETP (1981)
V.L. Alperovich, A. Minaev, A.S. Terekhov, JETP Lett. (1979)
V.L. Alperovich, V.I& Belinicher, V.N. Novikov, A.S. Terekhov, JETP (1981)
V.L. Gurevich, R. Laiho, Phys. Rev. B (1993)
C.B. Schmidt, S. Priyadarshi, S.A.T., M. Bieler, Phys. Rev. B (2015)
G.M. Mikheev, A.S. Saushin, V.M. Styapshin, Y.P. Svirko, Sci. Rep. (2018)

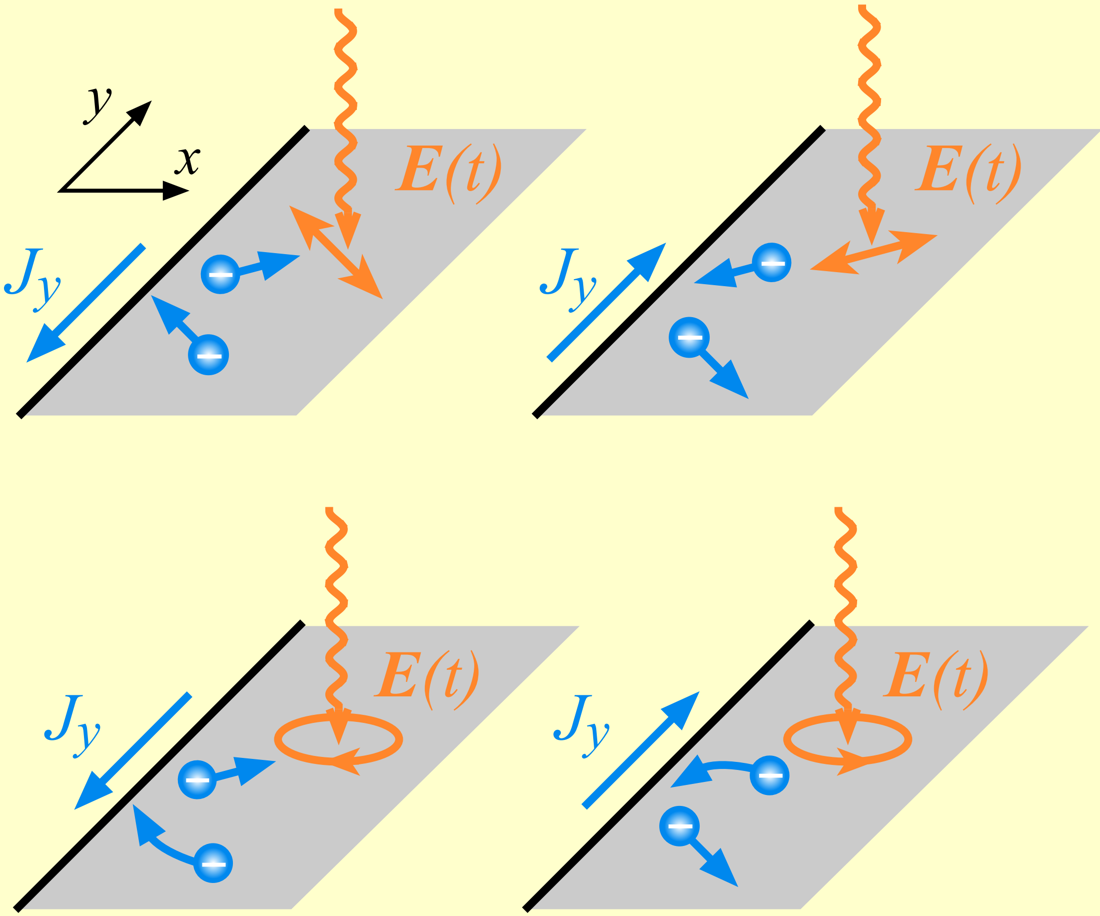
Edge plasmons

D.B. Mast, A.J. Dahm, and A.L. Fetter, Phys. Rev. Lett. (1985)
V.A. Volkov, S.A. Mikhailov, JETP Lett. (1985), JETP (1988)
I.V. Kukushkin, M.Yu. Akimov, J.H. Smet, S.A. Mikhailov, K. von Klitzing, I.L. Aleiner, V.I. Falko, PRL (2004)
V.M. Muravev, P.A. Gusikhin, A.M. Zarezin, I.V. Andreev, S.I. Gubarev, and I.V. Kukushkin, PRB (2019)
A.A. Zabolotnykh, V.A. Volkov, Phys. Rev. B (2019)

Review on edge photogalvanic effects in topological insulators

M.V. Durnev and S.A.T., Ann. Phys. **531**, 1800418 (2019)

EDGE CURRENTS EXCITED BY LINEARLY AND CIRCULARLY POLARIZED RADIATION



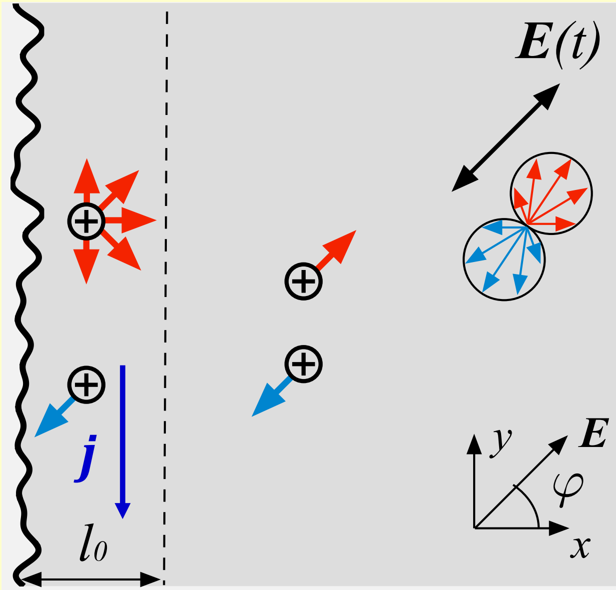
Linearly polarized radiation

$$J_y \propto (E_x E_y^* + E_y E_x^*)$$
$$\propto \sin 2\varphi$$

Circularly polarized radiation

$$J_y \propto i(E_x E_y^* - E_y E_x^*)$$
$$\propto P_{\text{circ}}$$

QUASI-CLASSICAL APPROACH



mean free path

Kinetic equation for distribution function

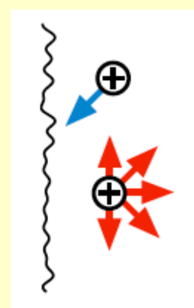
$f(\boldsymbol{p}, x, t)$

$$\frac{\partial f}{\partial t} + v_x \frac{\partial f}{\partial x} + e\boldsymbol{\mathcal{E}}(x,t) \cdot \frac{\partial f}{\partial \boldsymbol{p}} = \mathrm{I}\{f\}$$

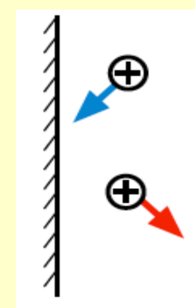
Electric field (external field + screening)

$$\mathcal{E}_{\omega,x}(x) = E_{\omega,x} + \frac{2}{\epsilon}\int_0^\infty \frac{\rho_\omega(x')dx'}{x - x'}, \quad \mathcal{E}_{\omega,y} = E_{\omega,y}$$

\+ Boundary condition at $x = 0$



diffusive scattering



specular reflection

Polarization dependence

$$J_y \propto E_x E_y \propto \sin 2\varphi$$

SOLUTION OF THE KINETIC EQUATION

Expansion in the Fourier series

$$f(\boldsymbol{p},x,t) = f_0 + \left[f_1(\boldsymbol{p},x)e^{-i\omega t} + \text{c.c.}\right] + f_2(\boldsymbol{p},x) + \ \ldots$$

$$f_1 \propto E \qquad\qquad f_2 \propto EE^*$$

The density of dc electric current and the total dc current

$$j_y(x) = e\nu \sum_p v_y f_2(x,\boldsymbol{p}) \qquad\qquad J_y = \int_0^\infty j_y(x)dx$$

the spin and valley degeneracy

The edge current

$$J_y = -e\nu\tau \sum_p v_x v_y [f_2(\boldsymbol{p},\infty) - f_2(\boldsymbol{p},0)] + i\frac{e^2\nu\tau}{\omega m^*}\sum_{\boldsymbol{p}} v_x\left[E_y f_1^*(\boldsymbol{p},\infty) - \text{c.c.}\right]$$

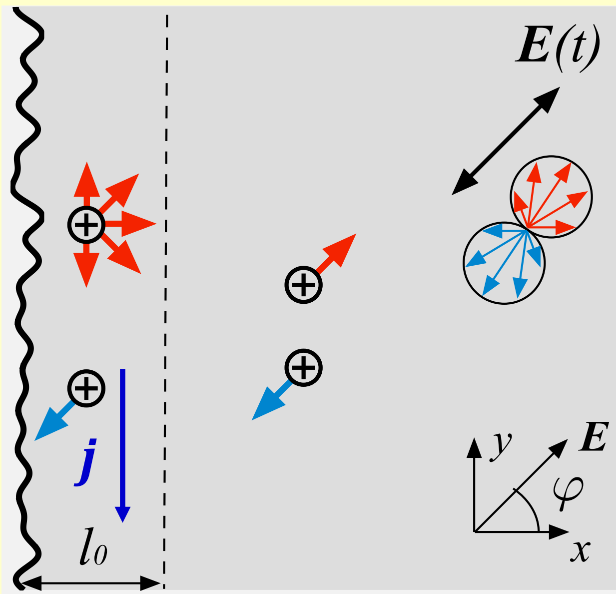
S. Candussio, M.V. Durnev, J. Yin, J. Keil, Y. Yang, S.-K. Son, A. Mishchenko, H. Plank, V.V. Bel’kov, S. Slizovskiy, S.A.T., V. Fal’ko, and S.D. Ganichev, PRB **102**, 045406 (2020)

M.V. Durnev and S.A.T., Phys. Status Solidi B **258**, 2000291 (2021)

CONTRIBUTIONS TO EDGE CURRENT

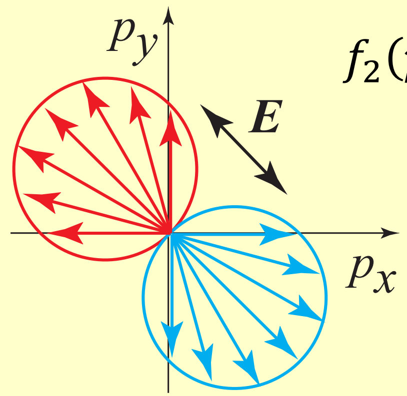
$$J_y = -e\nu\tau \sum_p v_x v_y [f_2(\boldsymbol{p},\infty) - f_2(\boldsymbol{p},0)] + i\,\frac{e^2\nu\tau}{\omega m^*} \sum_{\boldsymbol{p}} v_x \left[E_y f_1^*(\boldsymbol{p},\infty) - \text{c.c.}\right]$$

Alignment of electron momenta by linearly polarized radiation



mean free path

Anisotropic part of the distribution function



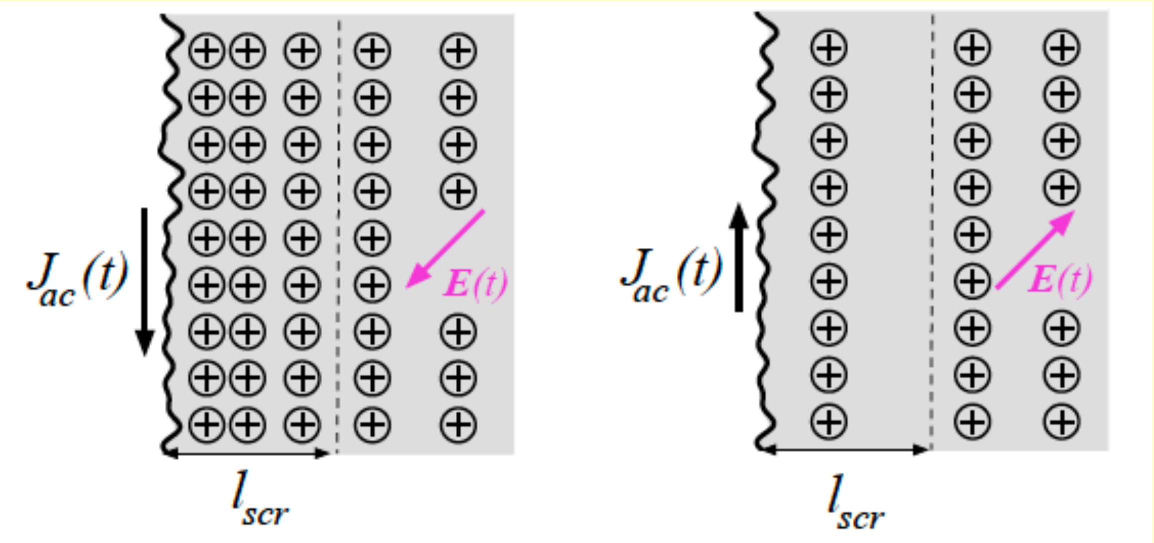
$$f_2(\boldsymbol{p},\infty) \propto \sum_{\alpha,\beta} \left(p_\alpha p_\beta - \frac{p^2}{2}\right) E_\alpha E_\beta$$

2nd angular harmonic in ***p***-space

CONTRIBUTIONS TO EDGE CURRENT

$$J_y = -e\nu\tau \sum_p v_x v_y [f_2(\boldsymbol{p},\infty) - f_2(\boldsymbol{p},0)] + i\,\frac{e^2\nu\tau}{\omega m^*} \sum_{\boldsymbol{p}} v_x \left[E_y f_1^*(\boldsymbol{p},\infty) - \mathrm{c.\,c.}\right]$$

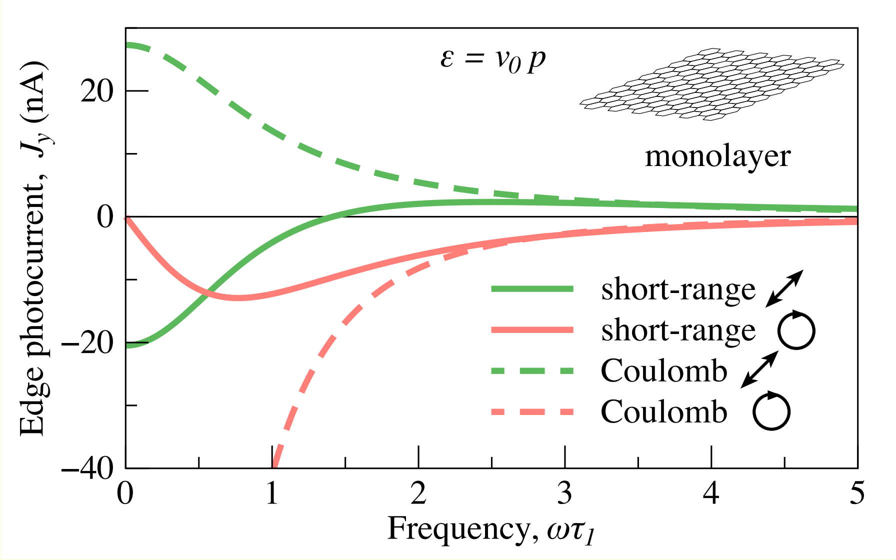
Dynamic accumulation of carriers at the edge



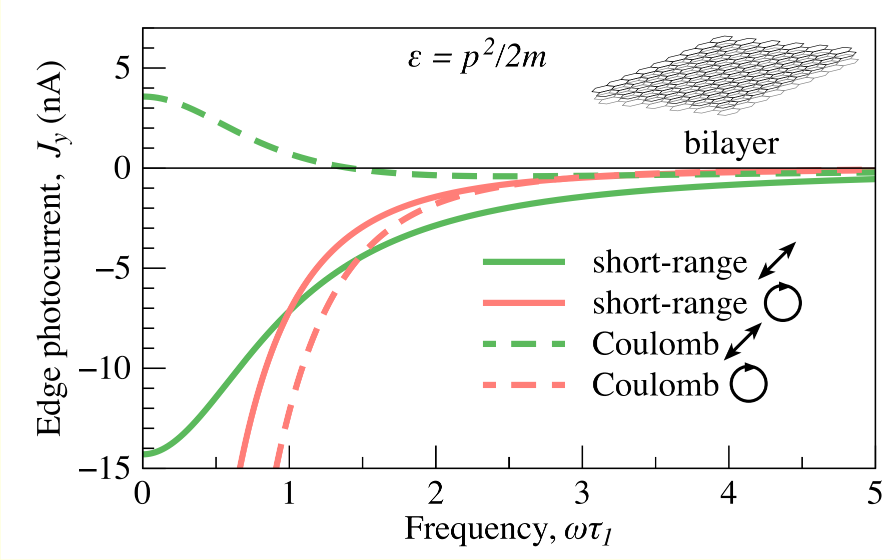
screening length

LINEAR VS PARABOLIC ENERGY SPECTRA

Edge currents in 2D systems with linear (graphene) and parabolic (bilayer) spectra



Graphene with the carrier density n = 5*10[11] cm[-2], relaxation time τ_1 = 1 ps, and the intensity I = 1 W/cm[2]



Bilayer with the carrier density n = 5*10[11] cm[-2], relaxation time τ_1 = 1 ps, and the intensity I = 1 W/cm[2]

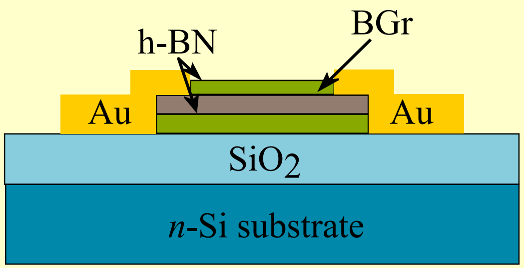
Edge current (specular reflection from the edge)

$$J_y = \frac{e\mathrm{Re}\,\sigma(\omega)}{m}\left\{\tau_1(\tau_1 - 2\tau_2) + \frac{m^2 v^2}{2}\left[\frac{\tau_1}{2}\left(\frac{\tau_1}{m}\right)' - m\left(\frac{\tau_1\tau_2}{m^2}\right)'\right] + \frac{m^2 v^2(\tau_1+\tau_2)}{4[1+(\omega\tau_2)^2]}\left(\frac{\tau_1}{m}\right)'\right\} S_2$$
$$- \frac{e\mathrm{Re}\,\sigma(\omega)}{m\omega}\left[\tau_1 + \frac{m^2 v^2[2+\omega^2\tau_2(\tau_2-\tau_1)]}{4[1+(\omega\tau_2)^2]}\left(\frac{\tau_1}{m}\right)'\right] S_3.$$

M.V. Durnev and S.A.T., Appl. Sci. **13**, 4080 (2023)

SAMPLES: GRAPHENE MONOLAYERS AND BILAYERS

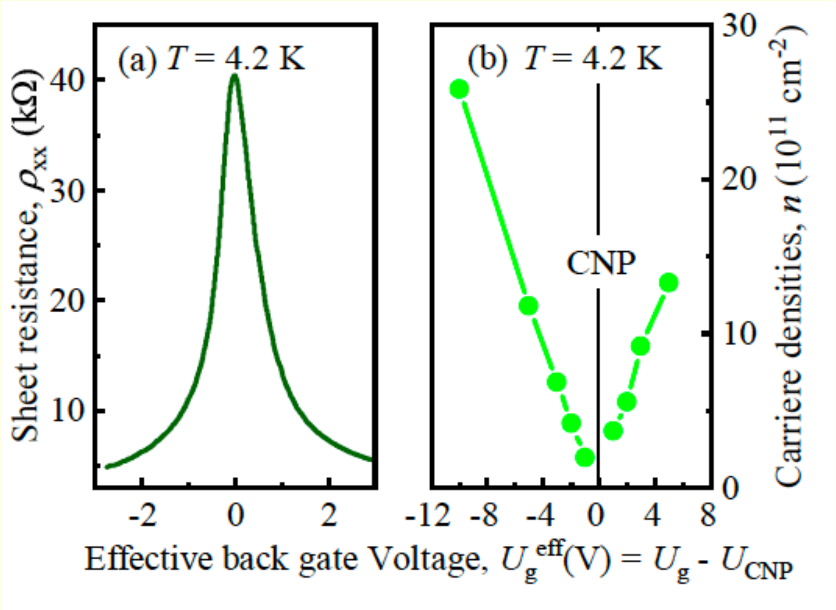
Sketch of samples



- exfoliated mono and bilayers/ h-BN
- epitaxial graphene on SiC
- contacts, Hall bar structure
- back gate to tune the Fermi level

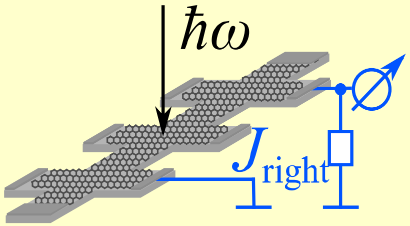
Samples: Regensburg, Goteborg, Manchester

Transport data. Dependence on gate voltage in graphene bilayer



EXPERIMENTAL TECHNIQUE

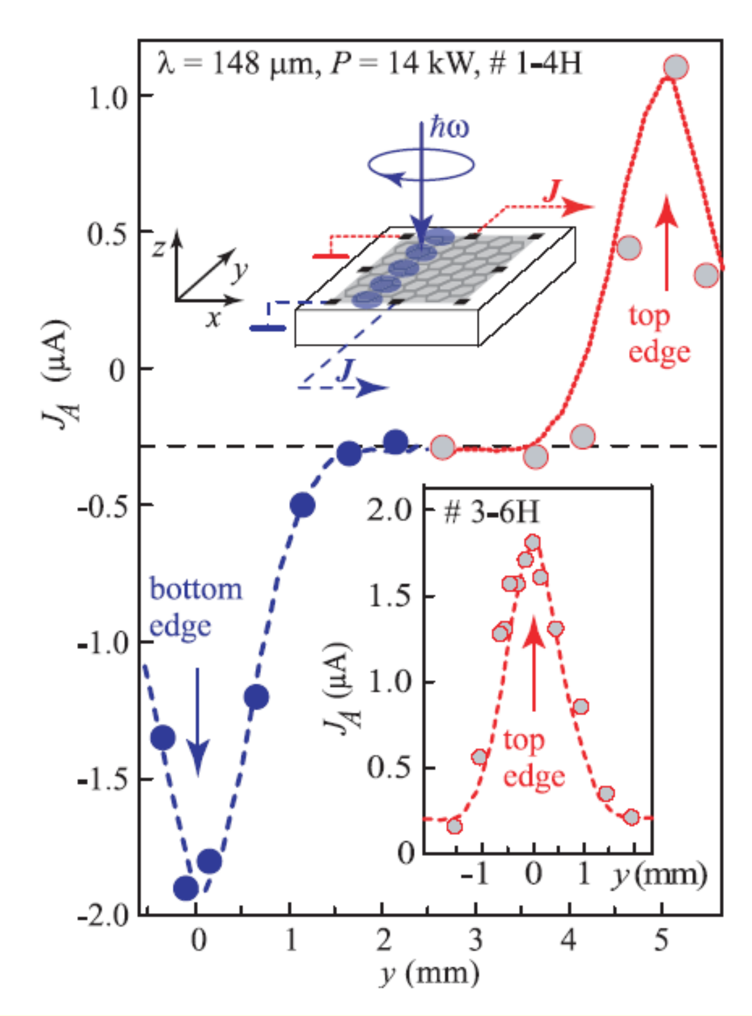
Experimental geometry



- pulsed molecular THz laser
- $f = 0.6, 0.8, 1.1, 2.0,$ and 3.3 THz

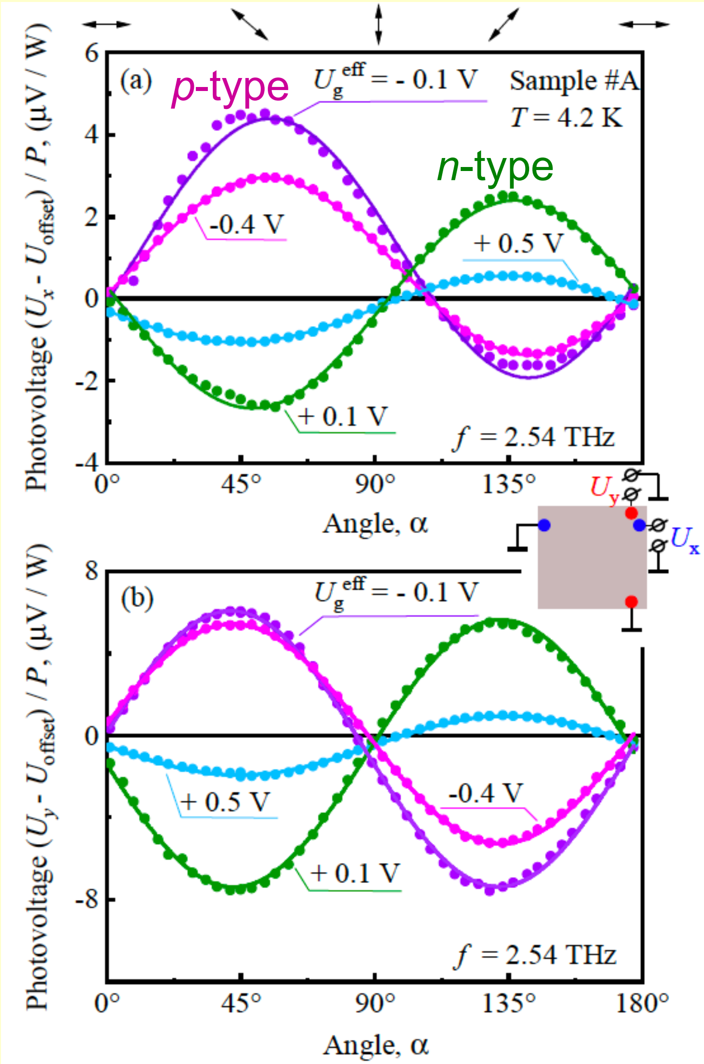
Experiment: Regensburg

Photoresponse vs laser spot position



large-scale epitaxial graphene

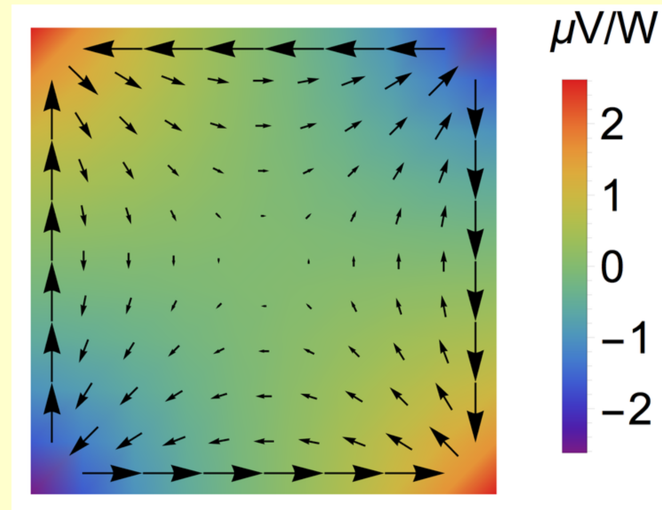
PHOTOVOLTAGE IN SQUARE-SHAPE BILAYER SAMPLE

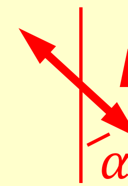


Electrostatic potential distribution

$$\mathrm{div}\left(\boldsymbol{j}_{\mathrm{photo}} + \boldsymbol{j}_{\mathrm{drift}}\right) = 0$$

$$\boldsymbol{j}_{\mathrm{drift}} = \sigma \boldsymbol{E} = -\sigma\, \mathrm{grad}\, \Phi$$



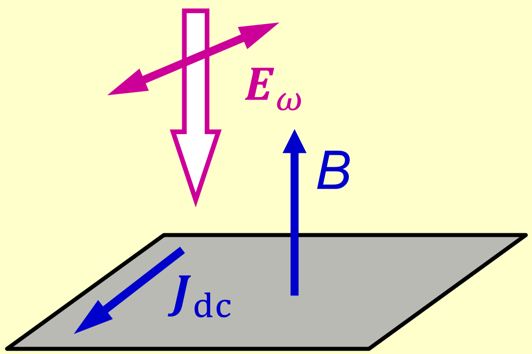


Edge electric current

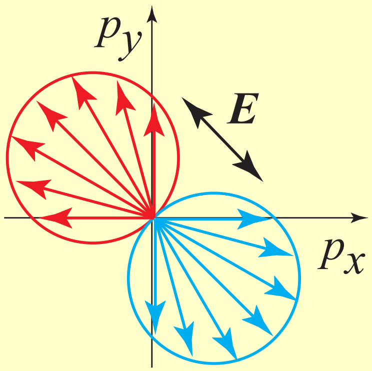
$$J_y = -\frac{2e^3\tau^3\, n_e\, E_x E_y}{m^{*2}[1+\omega^2\tau^2]} \propto \sin 2\alpha$$

S. Candussio, M.V. Durnev, J. Yin, J. Keil, Y. Yang, S.-K. Son, A. Mishchenko, H. Plank, V.V. Bel'kov, S. Slizovskiy, S.A.T., V. Fal'ko, and S.D. Ganichev, PRB **102**, 045406 (2020)

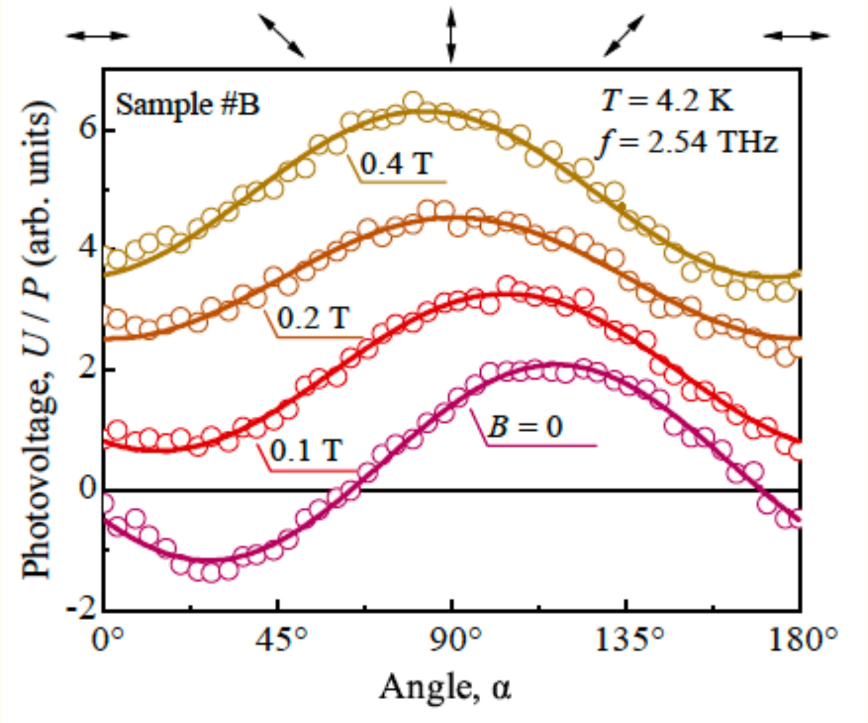
EFFECT OF MAGNETIC FIELD



Rotation of momentum alignment



Dependence of the edge current on magnetic field



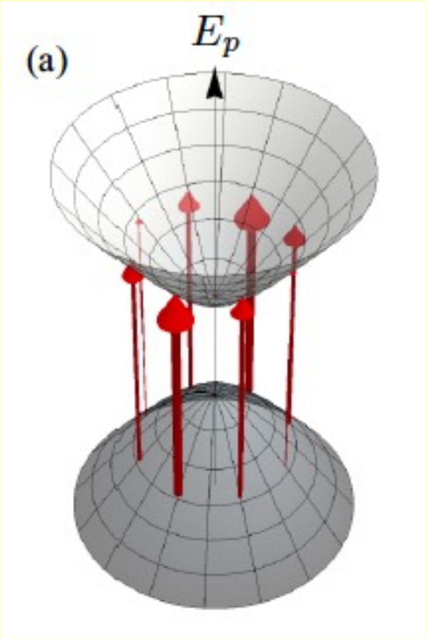
Edge photocurrent in classical magnetic field

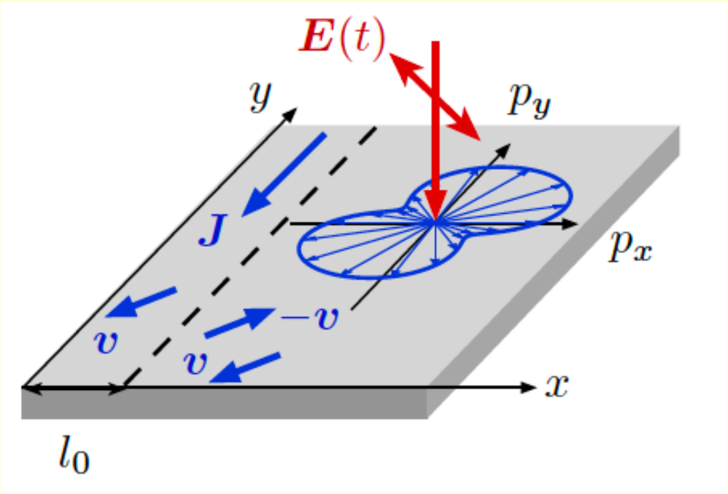
$$J_y = -\frac{e^3 \tau\, n_e}{m^{*2}\omega^2}\left[\frac{E_x E_y}{1+(2\omega_c\tau)^2} - \frac{\left(E_x^2 - E_y^2\right)\omega_c\tau}{1+(2\omega_c\tau)^2}\right] \propto \sin(2\alpha + \alpha_0)$$

↑ cyclotron frequency

$@\ \omega \gg \omega_c, 1/\tau$

EDGE PHOTOCURRENT AT INTER-BAND TRANSITIONS





Strong absorption and optical alignment of electron momenta at inter-band transitions in 2D Dirac materials

Optical alignment in bulk zinc-blende crystals and quantum wells:

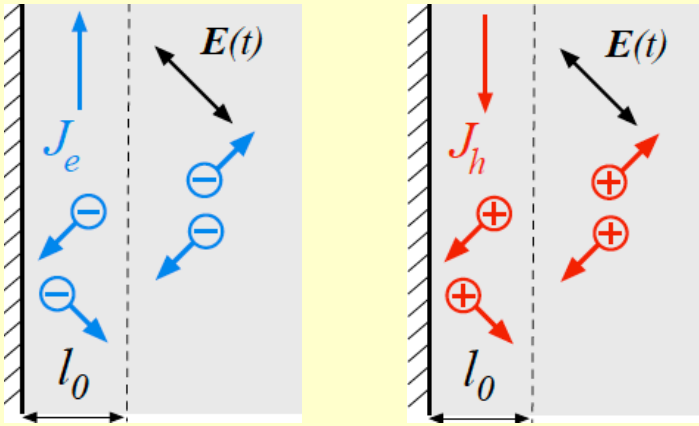
D.N. Mirlin, in *Optical orientation* (North-Holland, 1984)
V.I. Zemskii, B.P. Zakharchenya, D.N. Mirlin, JETP Lett. (1976)
V.D. Dymnikov, M.I. D'yakonov, and V.I. Perel, JETP (1976)
N.A. Merkulov, V.I. Perel, and M.E. Portnoi, JETP (1991)

Optical alignment in graphene:

R.R. Hartmann and M.E. Portnoi, (LAP Lambert Academic, Chisinau, 2011)
L.E. Golub, S.A.T., M.V. Entin, L.I. Magarill, Phys. Rev. B 84, 195408 (2011)

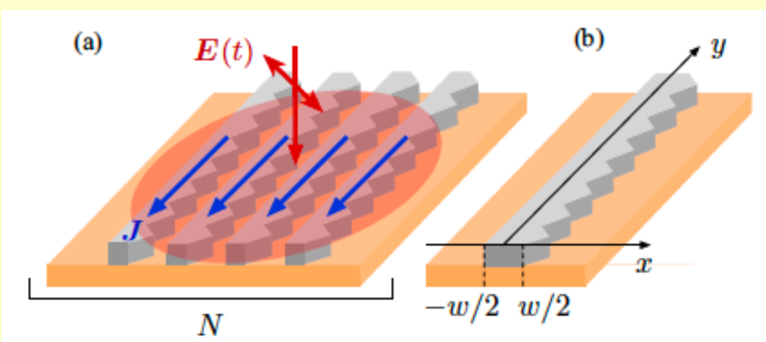
EDGE PHOTOCURRENT AT INTER-BAND TRANSITIONS

Edge photocurrents of electrons and holes



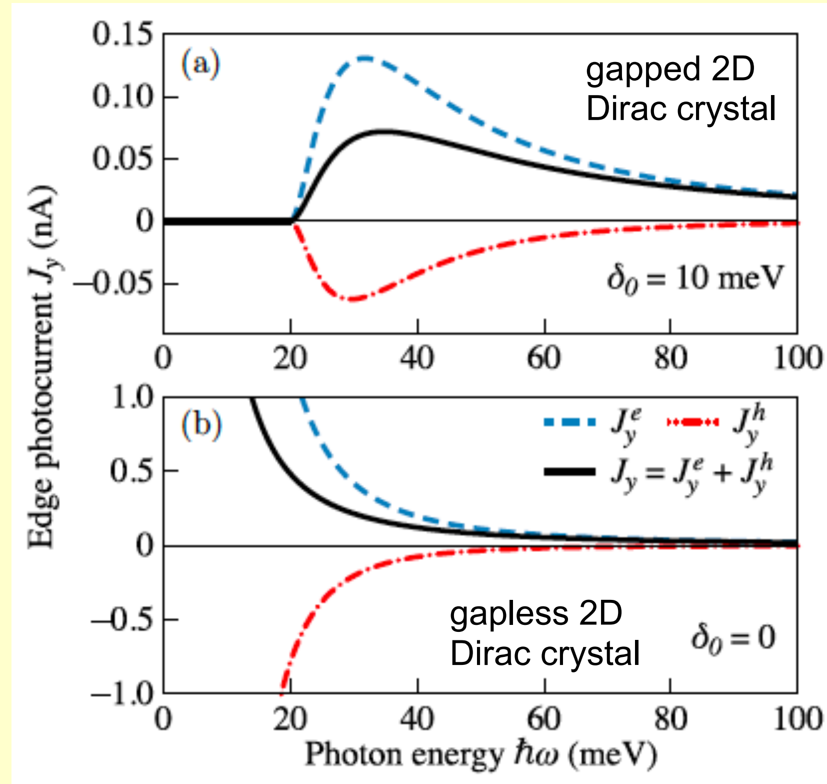
electron-hole asymmetry is required
for the electric current to emerge

Structure with many narrow strips



projection to 1 μA per W/cm² in 3×3 mm² sample

Excitation spectrum of edge photocurrent



at radiation intensity 1 W/cm²
and momentum relaxation time 1 ps

M.V. Durnev and S.A.T., Phys Rev. B **103**, 165411 (2021)

ПЛАН ЛЕКЦИИ

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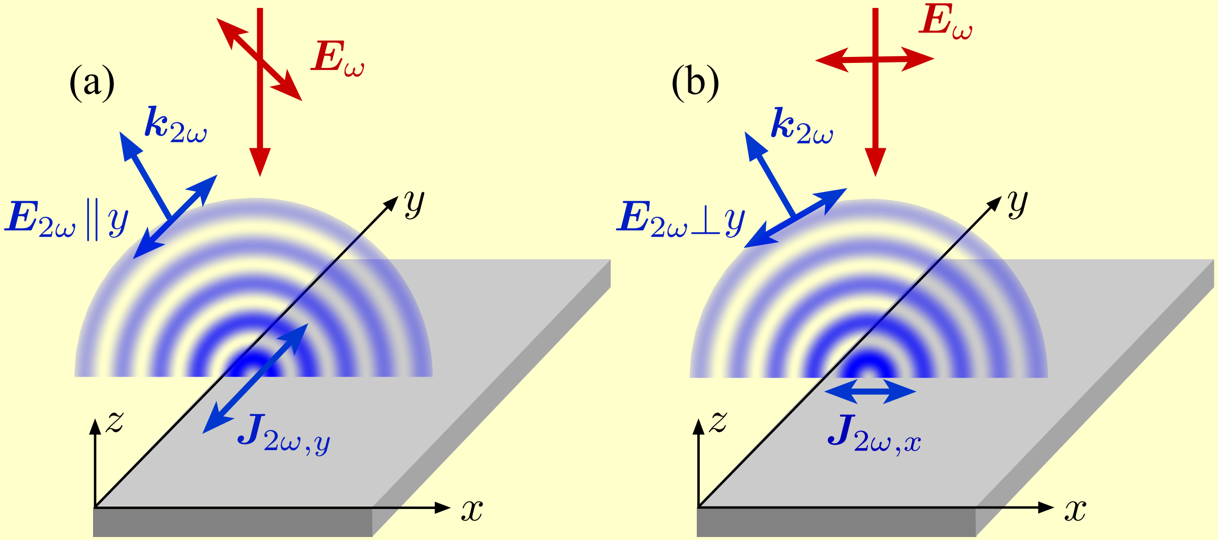
- Основные результаты

SECOND HARMONIC GENERATION



$J_{2\omega,y} \propto E_x E_y$

p-polarized emission

$J_{2\omega,x} \propto E_x^2$

s-polarized emission

AC electric field

$\boldsymbol{E}_\omega \exp(-i\omega t) + c.c.$

MICROSCOPIC THEORY OF EDGE SHG

Boltzmann equation for distribution function

$$\frac{\partial f}{\partial t} + v_x \frac{\partial f}{\partial x} + e\boldsymbol{\mathcal{E}}(x,t) \cdot \frac{\partial f}{\partial \boldsymbol{p}} = \mathrm{I}\{f\}$$

+ collision integral
+ boundary conditions

Electric field (external field + screening) at ω and 2ω

$$\mathcal{E}_{\omega,x}(x) = E_{\omega,x} + \frac{2}{\epsilon}\int_0^\infty \frac{\rho_\omega(x')dx'}{x-x'}, \quad \mathcal{E}_{2\omega,x}(x) = \frac{2}{\epsilon}\int_0^\infty \frac{\rho_{2\omega}(x')dx'}{x-x'}$$

Expansion in the Fourier series

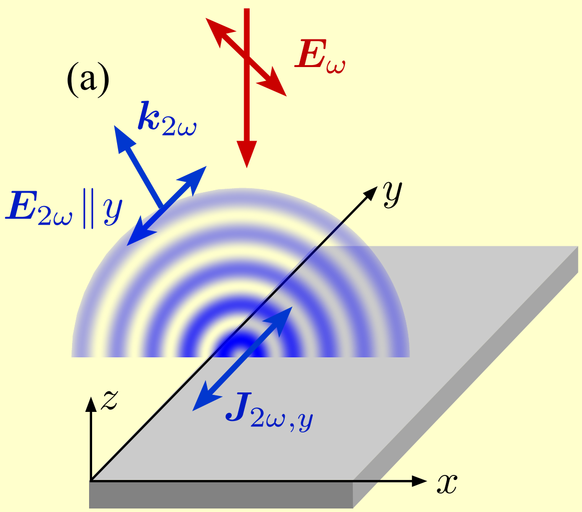
$$f(\boldsymbol{p},x,t) = f_0 + \left[f_1(\boldsymbol{p},x)e^{-i\omega t} + \mathrm{c.c.}\right] + \left[f_2(\boldsymbol{p},x)e^{-2i\omega t} + \mathrm{c.c.}\right] + \ \ldots$$

Currents at double frequency along and normal to edge

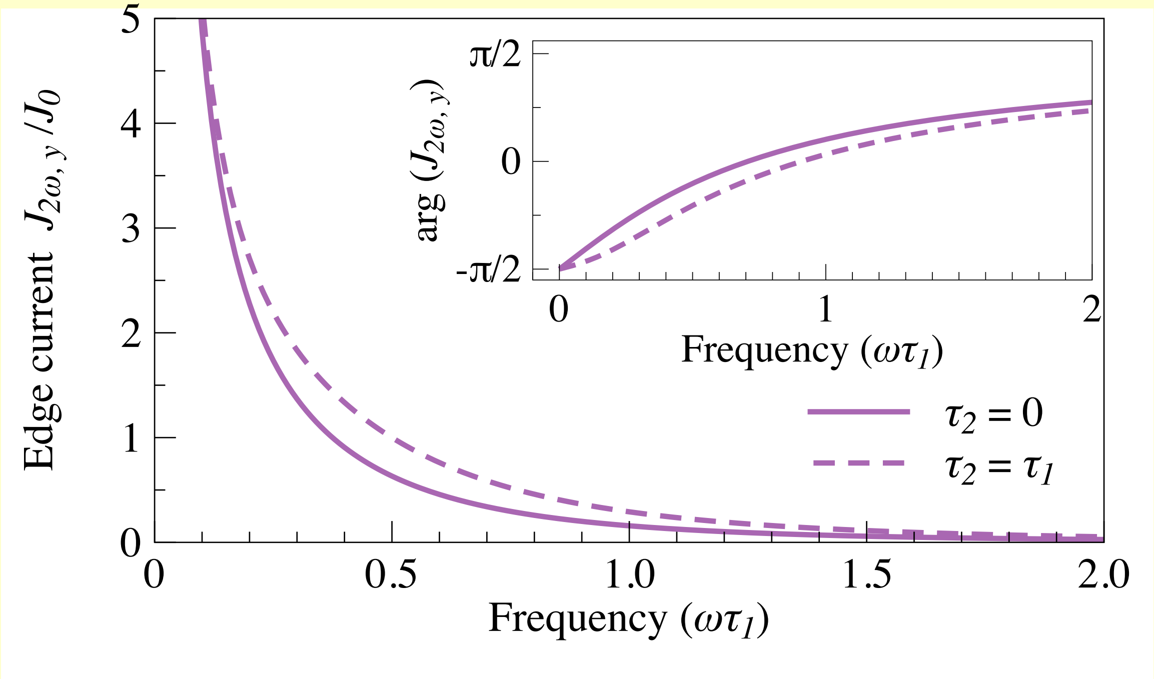
$$j_{2\omega,\parallel} = \frac{-e\nu\tau_1}{1-2i\omega\tau_1}\left[\sum_{\boldsymbol{p}} v_x v_y \frac{\partial f_2}{\partial x} - \frac{eE_{\omega,y}}{m}\sum_{\boldsymbol{p}} f_1\right]$$

$$j_{2\omega,\perp} = \frac{-e\nu\tau_1}{1-2i\omega\tau_1}\left[\sum_{\boldsymbol{p}} v_x^2 \frac{\partial f_2}{\partial x} - \frac{e\mathcal{E}_{\omega,x}}{m}\sum_{\boldsymbol{p}} f_1\right] + \frac{ne^2\tau_1}{1-2i\omega\tau_1}\,\mathcal{E}_{2\omega,x}$$

2ω CURRENT ALONG THE EDGE



Frequency dependence of the current at 2ω



Current along the edge

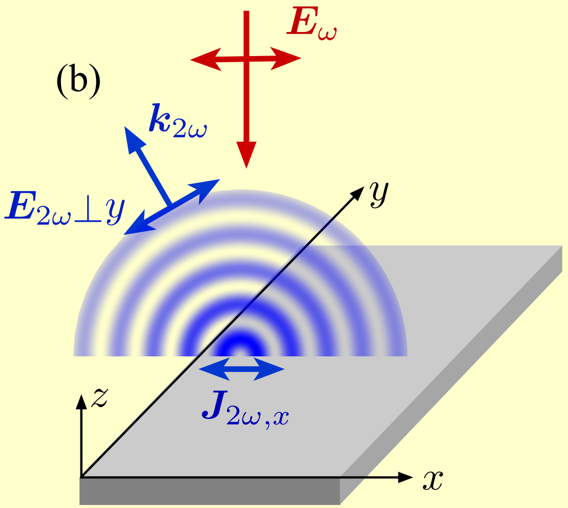
$$J_{2\omega,\parallel} = -i\frac{ne^3\tau_1(1-4i\omega\tau_2)}{m^{*2}\omega(1-i\omega\tau_1)(1-2i\omega\tau_1)(1-2i\omega\tau_2)}E_{\omega,x}E_{\omega,y}$$

τ_1, τ_2 are the relaxation times of first and second angular harmonics

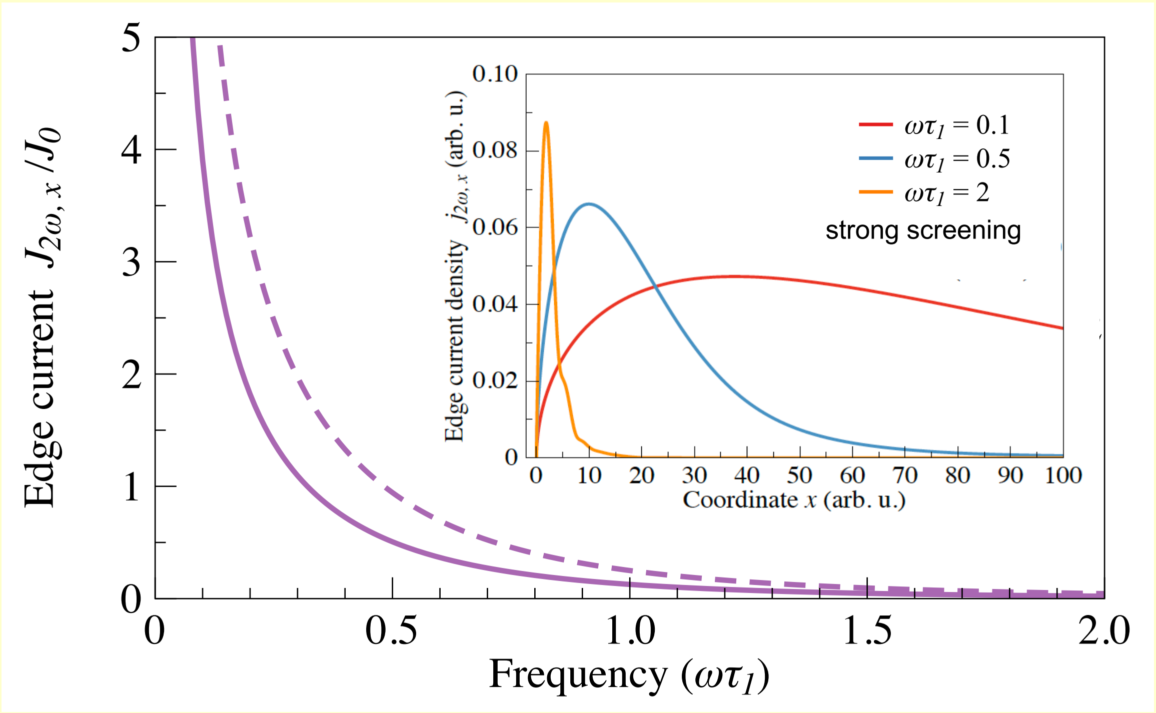
- The total current weakly depends on screening (while the current profile does depend)

M.V. Durnev and S.A.T., Phys Rev. B **106**, 125426 (2022)

2ω CURRENT PERPENDICULAR TO THE EDGE



Frequency dependence of the current and current profile



Numerical calculations for 2D system with parabolic spectrum:

—— strong screening (local response approximation)

- - - no screening

M.V. Durnev and S.A.T., Phys Rev. B **106**, 125426 (2022)

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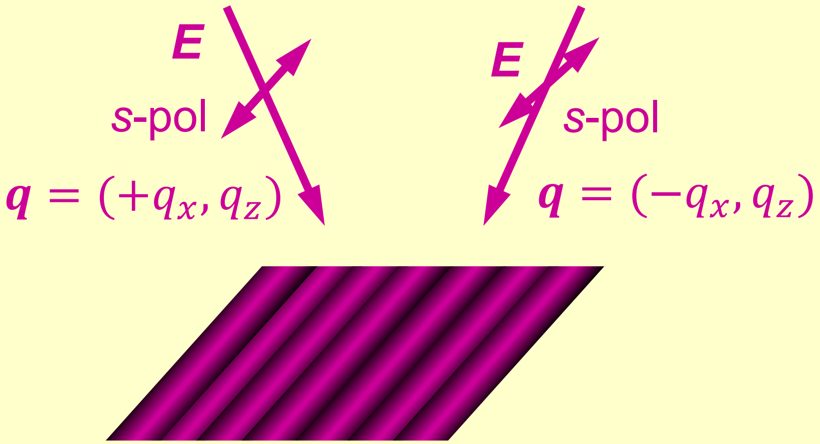
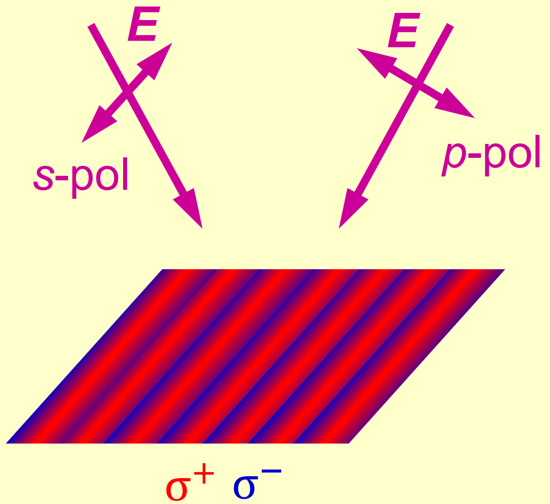
STRUCTURED RADIATION

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

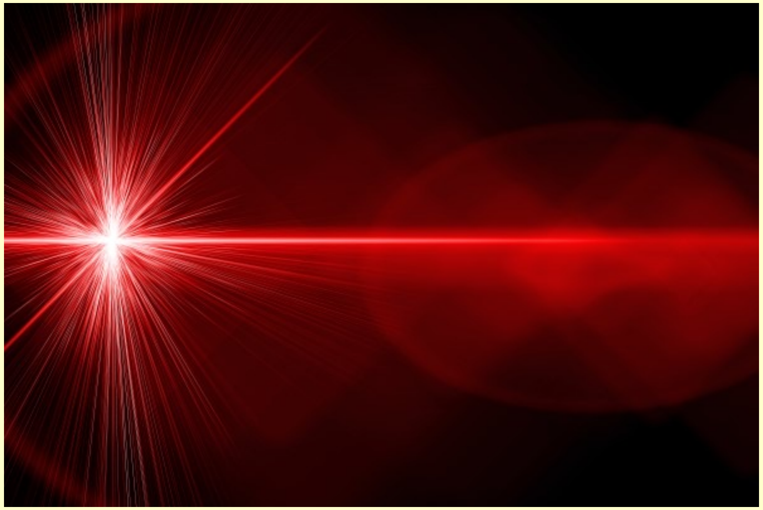


intensity grating

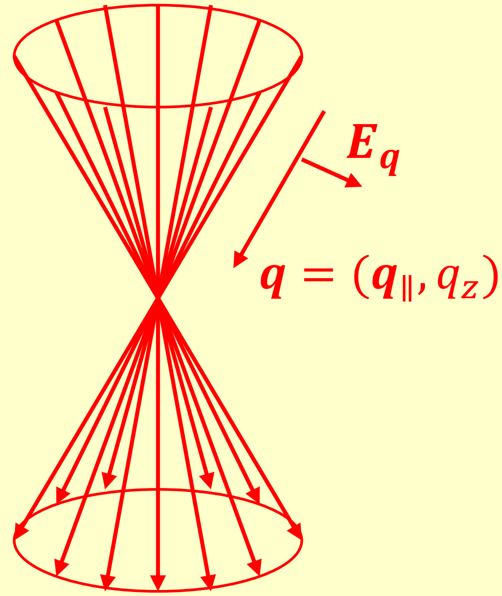


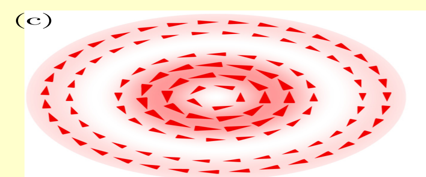
polarization grating

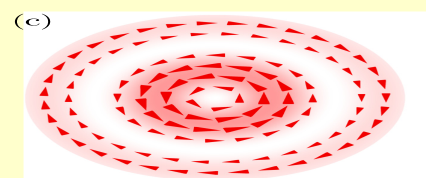
OPTICAL BEAMS



Bessel beams







Superposition of plane waves

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

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

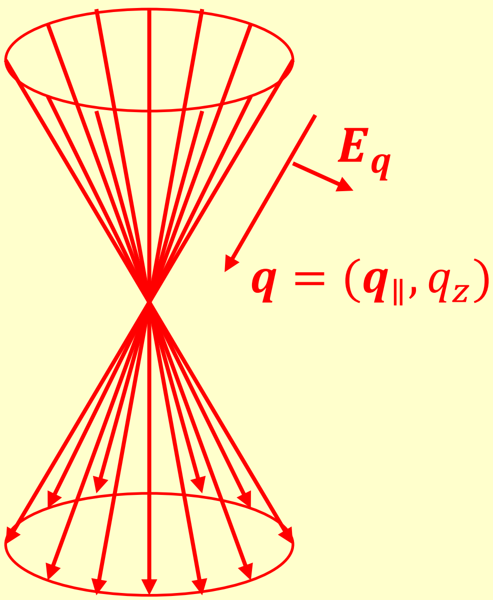
Paraxial approximation

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

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

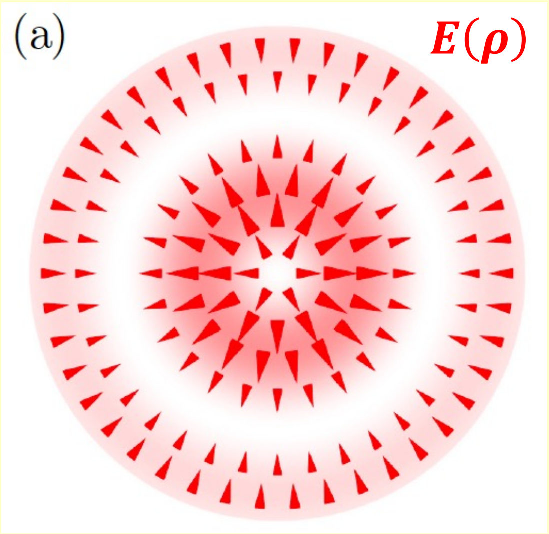
VECTOR BEAMS

Bessel beams

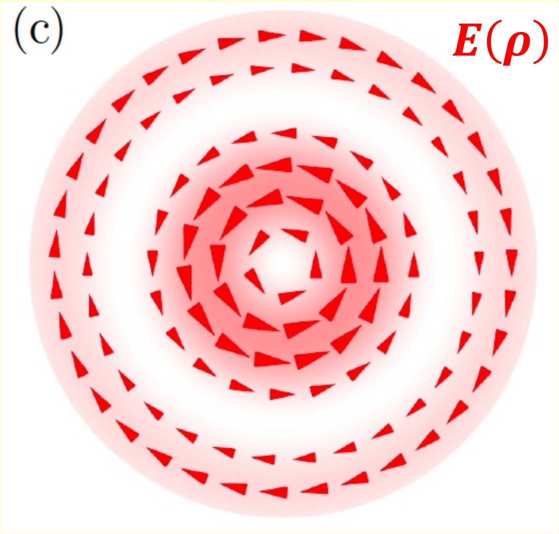


Electric field

(a) Radial beam



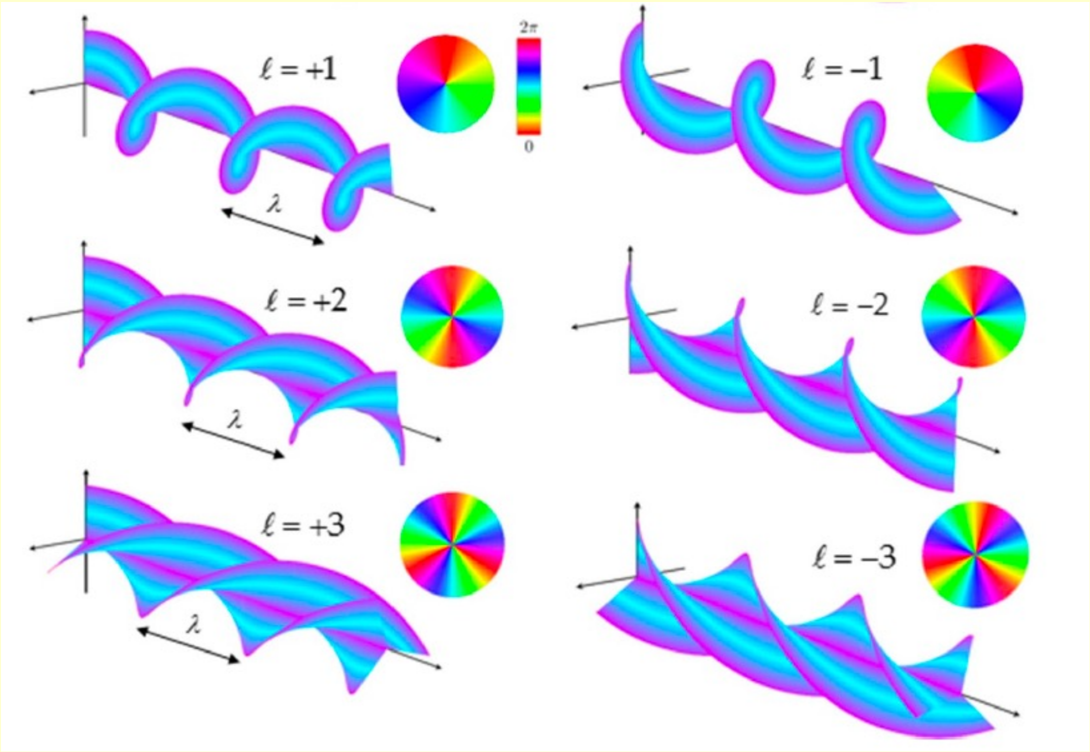
(c) Azimuthal beam



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

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

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

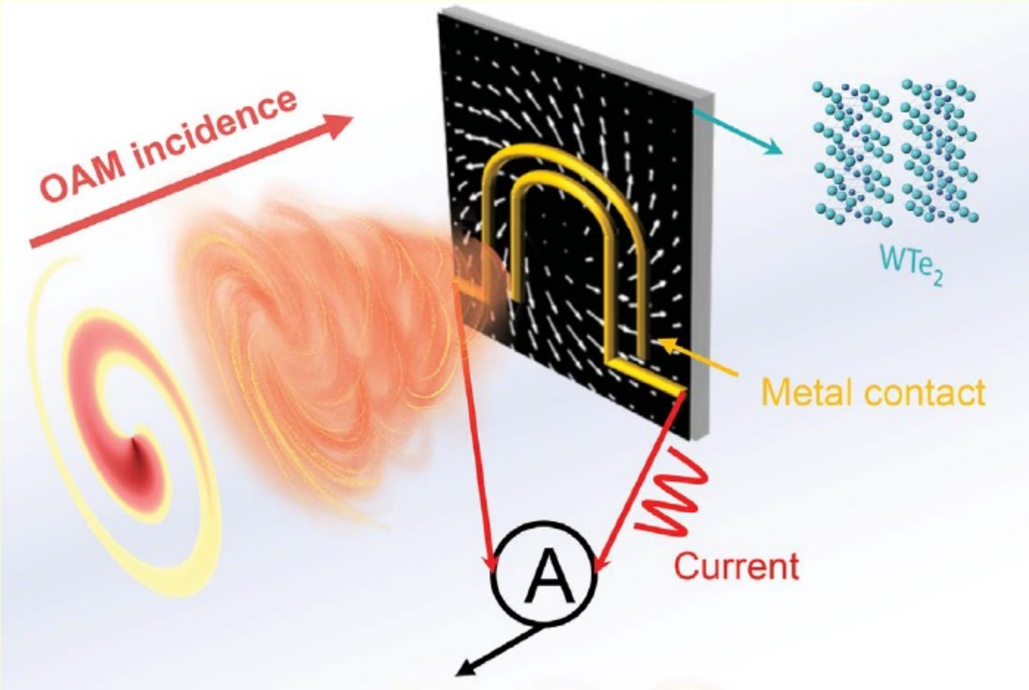
photons with OAM

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)

PHOTORESPONSE TO STRUCTURED RADIATION

Observation: Photoresponse sensitive to photon orbital angular momentum (OAM)

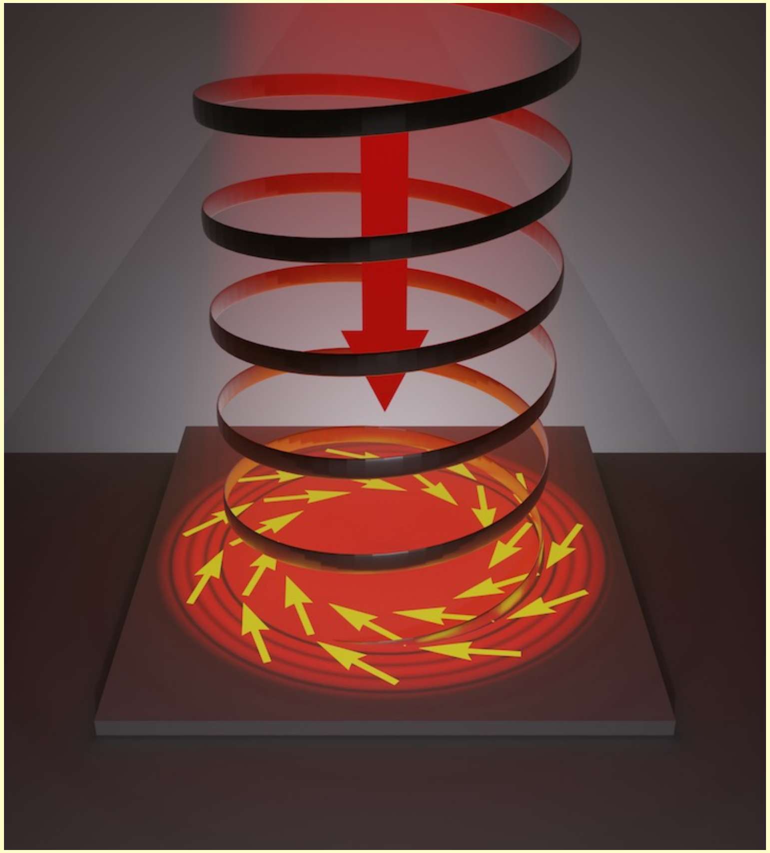


Z. Ji, W. Liu, S. Krylyuk et al., Science **368**, 763 (2020)

Open questions: Microscopic mechanisms, Theory

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

PHOTOCURRENTS BY STRUCTURED THZ 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

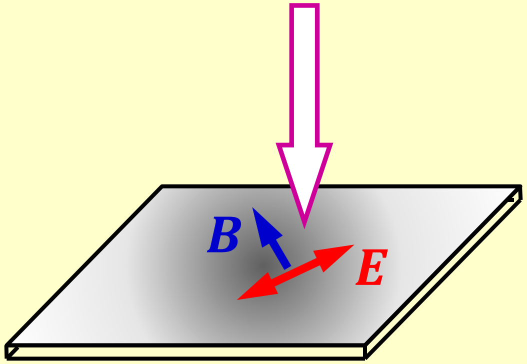
Emergent dc photocurrent $\boldsymbol{j}(\boldsymbol{r})$ due to ac field structure

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

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 $L\gg(2\pi\sigma/c)$

SOLUTION OF THE KINETIC EQUATION

Expansion in the field amplitude

$$f(\boldsymbol{p},\boldsymbol{r},t) = f_0(\boldsymbol{p}) + \left[f_1(\boldsymbol{p},\boldsymbol{r})e^{-i\omega t} + \mathrm{c.\,c.}\right] + f_2(\boldsymbol{p},\boldsymbol{r})$$

$$f_1 \propto E \qquad\qquad f_2 \propto EE^*, EB^*$$

Set of differential equations

$$-i\omega f_1 + \boldsymbol{v}\cdot\frac{\partial f_1}{\partial \boldsymbol{r}} + e\boldsymbol{E}_{\parallel}(\boldsymbol{r},t)\cdot\frac{\partial f_0}{\partial \boldsymbol{p}} = \mathrm{I}\{f_1\}$$

$$\boldsymbol{v}\cdot\frac{\partial f_2}{\partial \boldsymbol{r}} + e\left\{\left[\boldsymbol{E}_{\parallel}(\boldsymbol{r},t) + \frac{1}{c}\,\boldsymbol{v}\times\boldsymbol{B}_z(\boldsymbol{r},t)\right]\cdot\frac{\partial f_1^*}{\partial \boldsymbol{p}} + \mathrm{c.\,c.}\right\} = \mathrm{I}\{f_2\}$$

The density of dc electric current

$$\boldsymbol{j}(\boldsymbol{r}) = e\nu\sum_{\boldsymbol{p}}\boldsymbol{v}\,f_2(\boldsymbol{p},\boldsymbol{r})$$

ν is the spin and/or valley degeneracy

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

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

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

"Stokes" parameters

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

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

$S_2 = (E_x E_y^* + E_y E_x^*)$

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

(ii) Currents by phase gradient

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

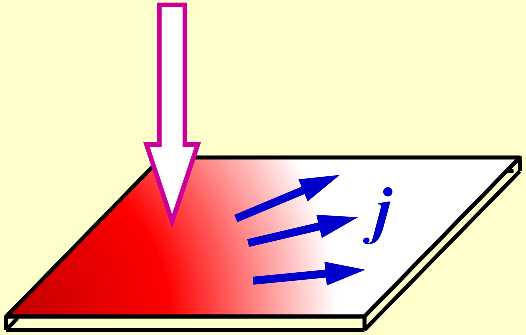
σ the high-frequency conductivity

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

$$\tau \text{ and } \tau_\varepsilon$$

(II) CURRENTS DRIVEN BY POLARIZATION GRADIENTS

Currents by polarization gradients

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

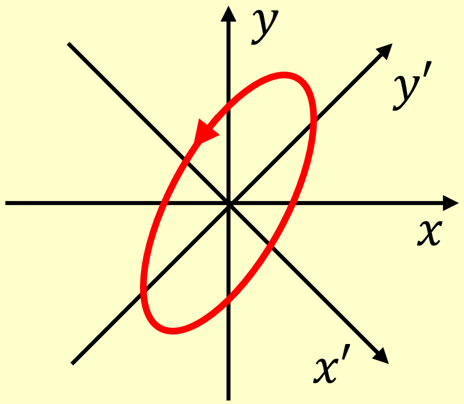
$$j_y^{(\mathrm{pol})} = -\frac{e\tau^2 \,\mathrm{Re}\,\sigma}{m^*}\left(\frac{\partial S_2}{\partial x} - \frac{\partial S_1}{\partial y} + \frac{1}{\omega\tau}\frac{\partial S_3}{\partial x}\right)$$

Polarization Stokes parameters

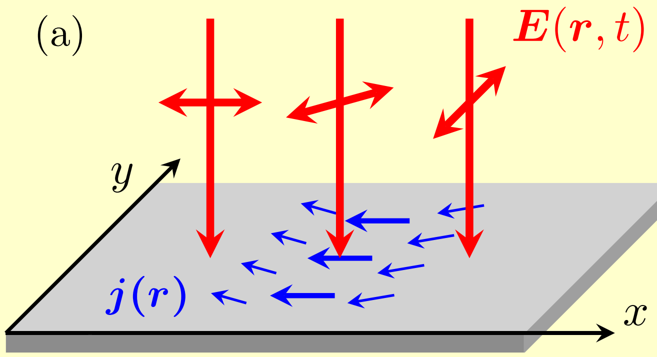
$$S_1 = |E_x|^2 - |E_y|^2 \propto P_{\mathrm{lin}}$$

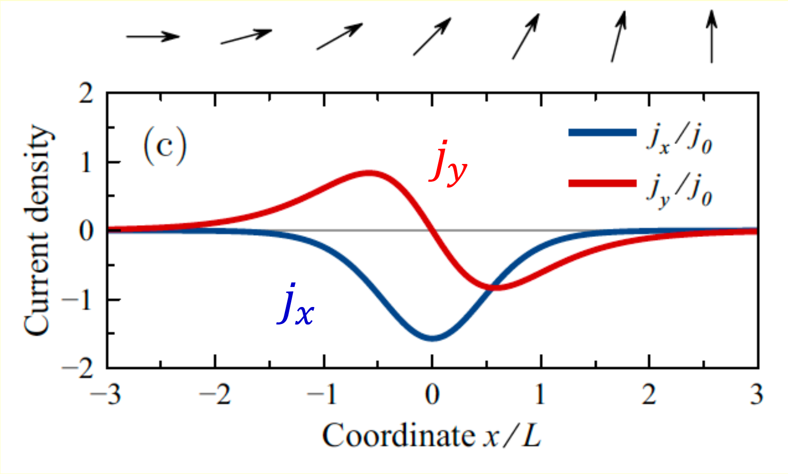
$$S_2 = \left(E_x E_y^* + E_y E_x^*\right) \propto P_{\mathrm{diag}}$$

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



PHOTOCURRENTS BY POLARIZATION GRADIENTS – I

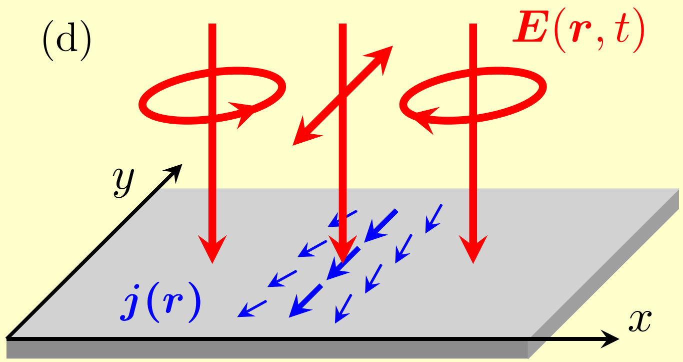


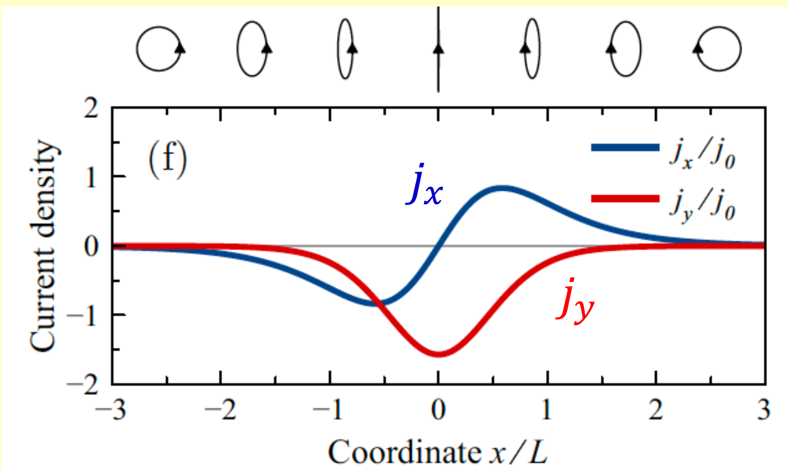


A.A. Gunyaga, M.V. Durnev, and S.A.T., Phys. Rev. B **108**, 115402 (2023)

Edge currents: M.V. Durnev and S.A.T., Appl. Sci. **13**, 4080 (2023)

PHOTOCURRENTS BY POLARIZATION GRADIENTS – II





Total current along the boundary between the domains excited by σ^+ and σ^- radiation

$$J_y = \int j_y(x)dx = -\frac{ne^3\tau^2[S_3(+\infty) - S_3(-\infty)]}{m^{*2}\omega(1+\omega^2\tau^2)}$$

Estimation $J_y \sim 20\ \mu\text{A}$

for $n = 5 \cdot 10^{11}\text{cm}^{-2}, \text{m}^* = 0.3\text{m}_0$
$\tau = 1\text{ ps}, \omega\tau = 1, \text{and } I = 1\text{ kW/cm}^2$

A.A. Gunyaga, M.V. Durnev, and S.A.T., Phys. Rev. B **108**, 115402 (2023)
Edge currents: M.V. Durnev and S.A.T., Appl. Sci. **13**, 4080 (2023)

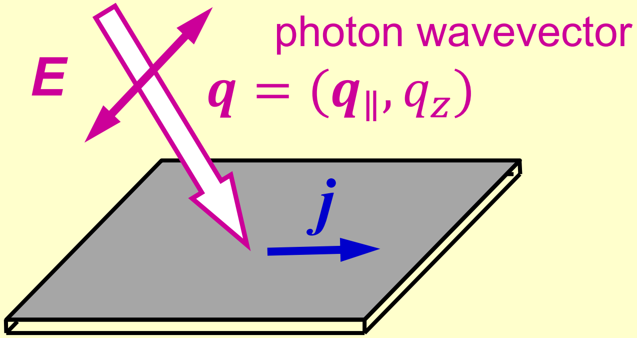
(II) CURRENTS DRIVEN BY PHASE GRADIENT

Currents by the gradient of the phase

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

$\propto \boldsymbol{\nabla}\varphi(\boldsymbol{r})$ 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

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

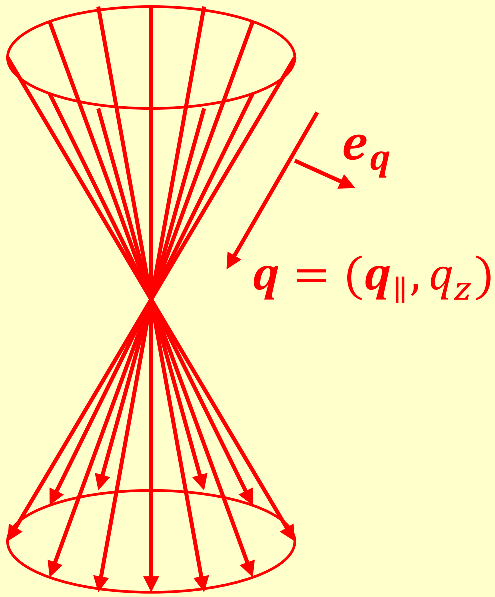
✓ Here,
generalized photon drag effect

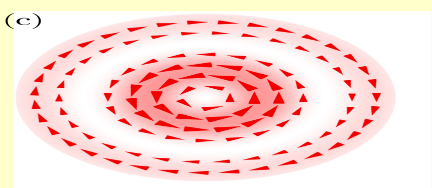
Photon drag:

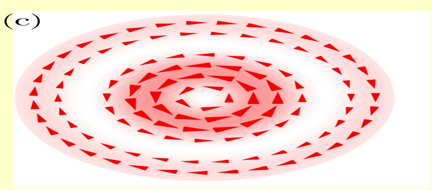
A.M. Danishevskii et al., JETP (1970)
A.F. Gibson et al., Appl. Phys. Lett. (1970)
V.I. Perel', Ya.M. Pinskii, Phys. Solid State (1973)
J. Karch et al., Phys. Rev. Lett. (2010)
M.V. Entin, L.I. Magarill, D.L. Shepelyansky, Phys. Rev. B (2010)

TWISTED RADIATION BEAMS

Bessel beams







Electric field decomposed over plane waves

$$\boldsymbol{E}(\boldsymbol{r}, z) = E_0 e^{iq_z z} \sum_{\boldsymbol{q}_\parallel} a(\boldsymbol{q}_\parallel) \exp\left(i\boldsymbol{q}_\parallel \cdot \boldsymbol{r}\right) \boldsymbol{e}_{\boldsymbol{q}}$$

$a(\boldsymbol{q}_\parallel) \propto \exp(im\varphi)$

$\boldsymbol{e}_{\boldsymbol{q}}$: polarization vector

m (integer) is the projection of total angular momentum

Electric field in the beam

$$E_r(r, \varphi) = \frac{E_0}{2} e^{im\varphi} [o_+ J_{m+1}(q_\parallel r) - o_- J_{m-1}(q_\parallel r)]$$

$$E_\varphi(r, \varphi) = \frac{E_0}{2i} e^{im\varphi} [o_+ J_{m+1}(q_\parallel r) + o_- J_{m-1}(q_\parallel r)]$$

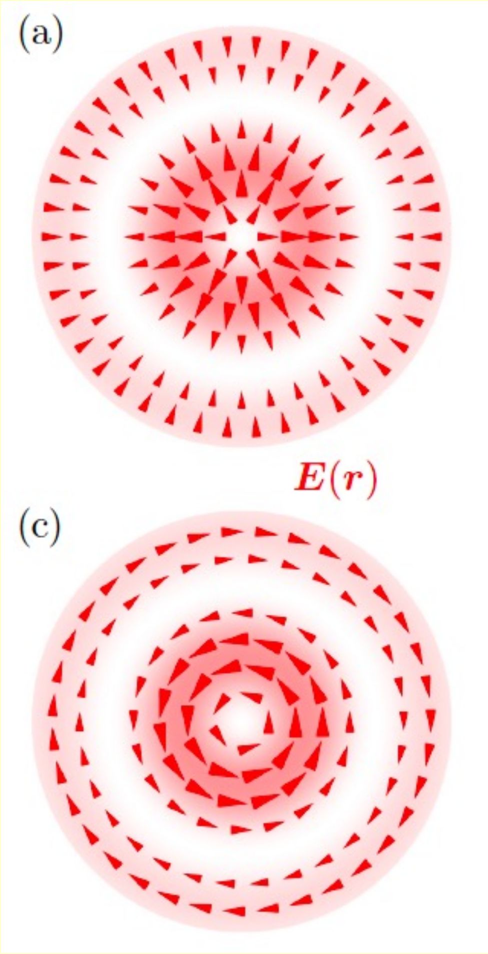
Bessel functions

see B. A. Knyazev and V. G. Serbo, Phys. Usp. **61**, 449 (2018)
G. Molina-Terriza, J. P. Torres, and L. Torner, Nat. Phys. **3**, 305 (2007)

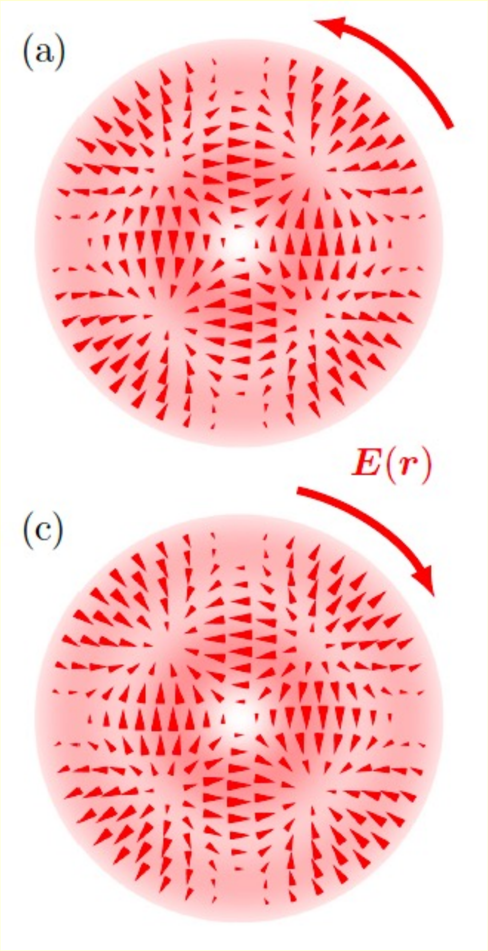
RADIAL AND AZIMUTHAL BESSEL BEAMS

Distribution of ***E*-field** in the cross-sections of the Bessel beams

Radial (composed of *p*-polarized waves) and azimuthal (of s-polarized waves) beams with $m = 0$

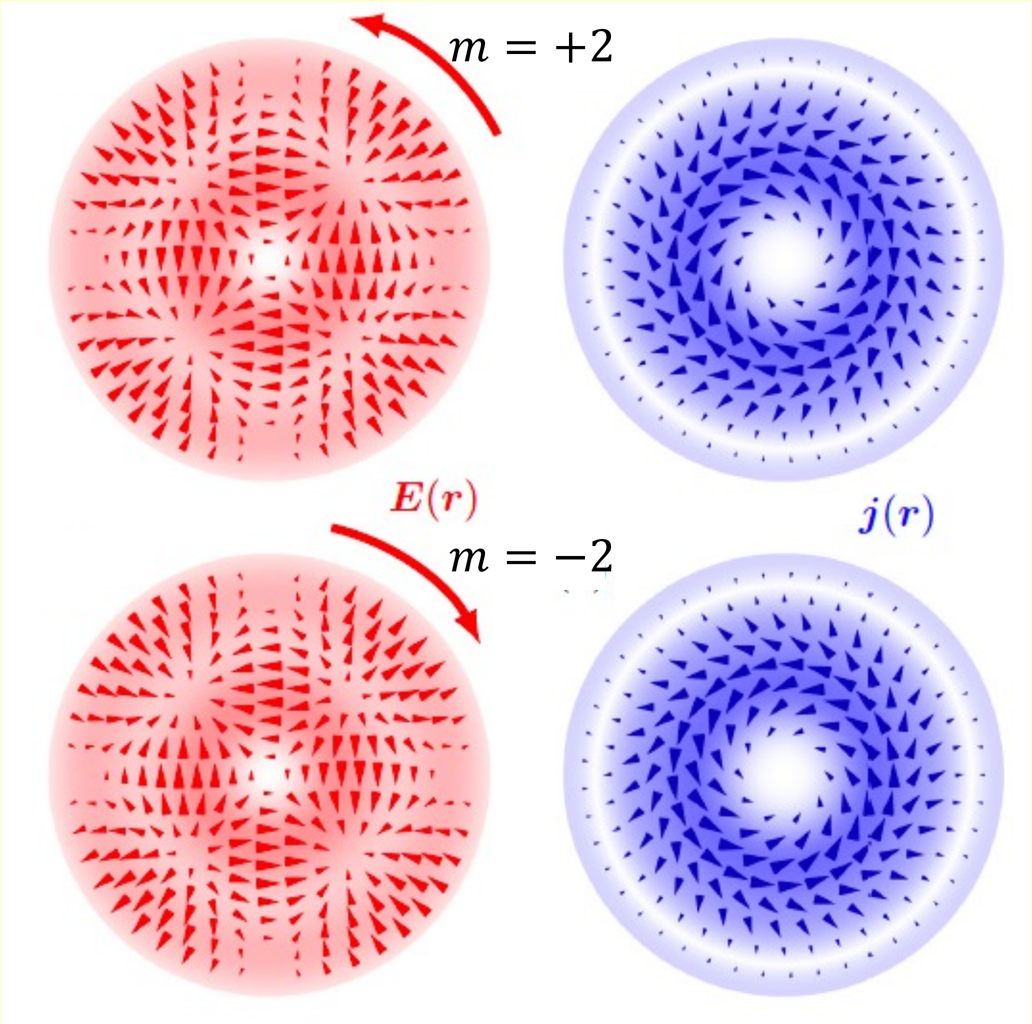


Radial beams with $m = \pm 2$



PHOTOCURRENTS BY BESSEL BEAMS

E-fields and Photocurrents 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

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

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

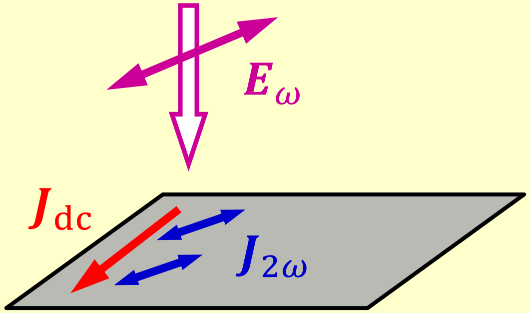
$$j_\varphi^{(\mathrm{pol})} + j_\varphi^{(\mathrm{ph})} = j_0 J_m (J_{m+1} - J_{m-1}) \left(p_2 + \frac{p_3}{\omega\tau} \right) - \frac{j_0}{\omega\tau} J_m (J_{m+1} + J_{m-1}),$$

Inverse Faraday effect of twisted light

Editors' Suggestion A.A. Gunyaga, M.V. Durnev, and S.A.T., Phys. Rev. B **108**, 115402 (2023)

ФОТОГАЛЬВАНИЧЕСКИЕ ЭФФЕКТЫ - 2. ГЕОМЕТРИЧЕСКИЕ ЭФФЕКТЫ

- ✓ Краевой фотогальванический эффект и краевой эффект генерации второй гармоники



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