Optical effects of pure spin currents

Ren-Bao Liu (刘仁保)

rbliu@phy.cuhk.edu.hk

Department of Physics, The Chinese University of Hong Kong

Collaborators: Jing Wang, Sheng-Nan Ji, Bang-fen Zhu (Tsinghua University, Beijing)

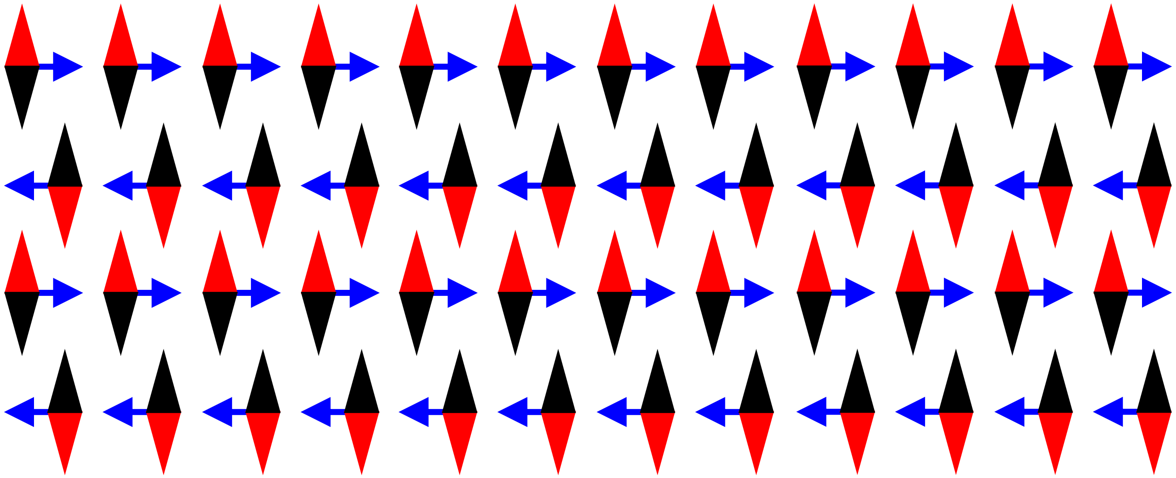
Outline:

- **Motivation**
- **Linear optics:** Faraday rotation w/o net magnetization
- **2nd order nonlinear optics**

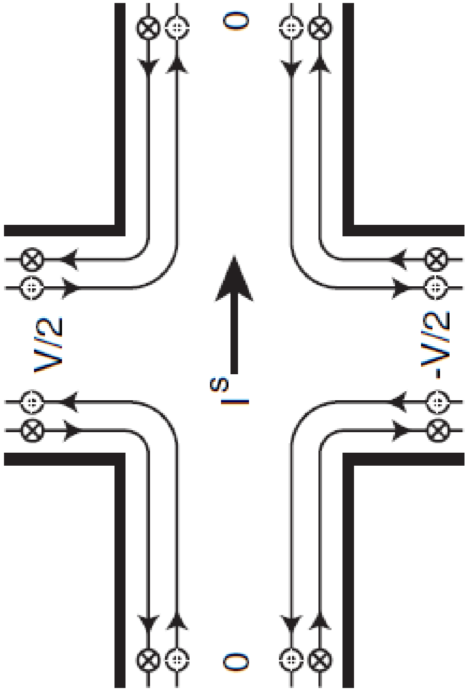
Supported by Hong Kong RGC HKU 10/CRF/08, Hong Kong GRF CUHK 402207, the NSFC Grant Nos. 10774086, 10574076 and the Basic Research Program of China Grant No. 2006CB921500

Pure spin current: Opposite spins go opposite

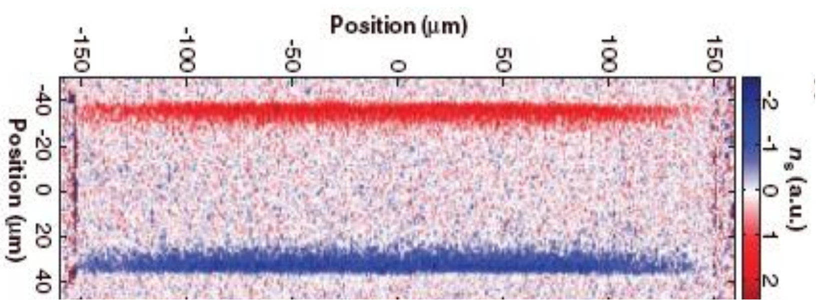
Information carriers in spintronics



Topological insulator
(PSC at edges)



Spin Hall effect (PSC in the bulk)



Y. K. Kato et al, Science **306**, 1910 (04)

Kane & Mele, PRL 95, 226801 (2005)

Motivation: How to measure PSC where & while it flows?

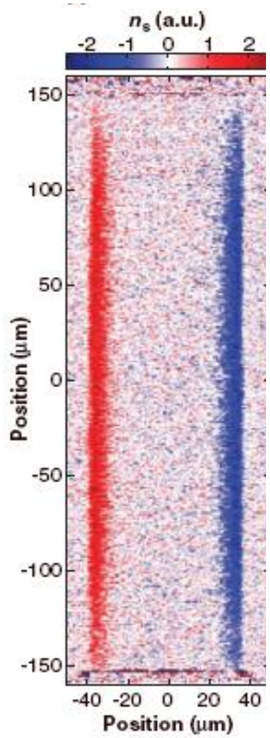
Smoking guns:

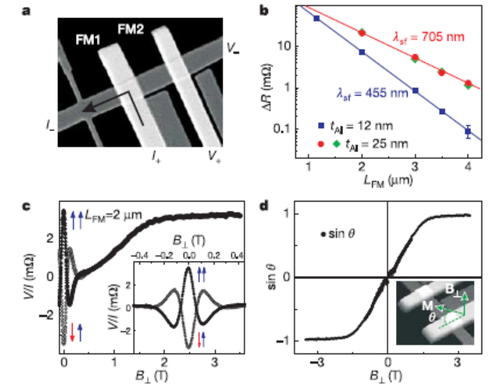
Spins accumulate at stopping edges:

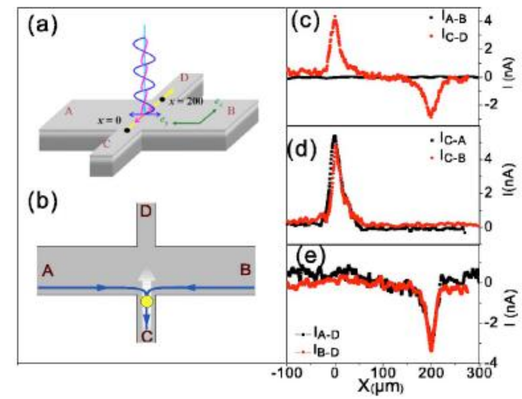
Y. K. Kato et al, Science **306**, 1910 (04);
J. Wunderlich et al, Phys. Rev. Lett. **94**, 047204 (05);
H. Zhao et al, Phys. Rev. Lett. **96**, 246601 (06);
…

Converted to electrical signals:

S. O. Valenzuela & M. Tinkham, Nature **442**,176 (06);
X. D. Cui et al, Appl. Phys. Lett. **90**, 242115 (07);
S. D. Ganichev et al, Phys. Rev. B **75**, 155317 (07);
…







No charge current, no magnetization, no direct EM induction.

How to see it where and while it flows?

Q: Can we directly measure a pure spin current?

Rule of thumb: Currents breaking the same symmetries are coupled

A pure spin current can be formulated as a rank-2 tensor

$$\mathbb{J} = \mathbf{J}\mathbf{Z},$$

$\mathbf{J}$: spin polarization

$\mathbf{Z}$: current flowing direction

Spin is a pseudo-vector

Broken & unbroken symmetries:

1. Time-reversal symmetry kept (T)
2. Space inversion broken (P)
3. Rotational symmetry broken (R)

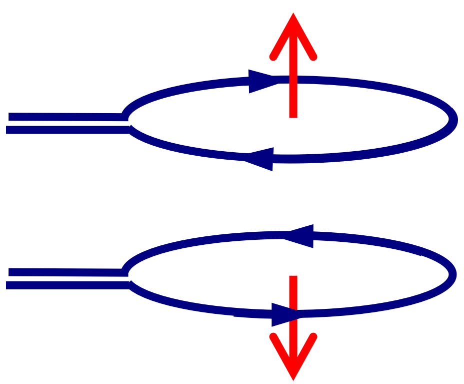
A clue: Ampere & Orsted effects

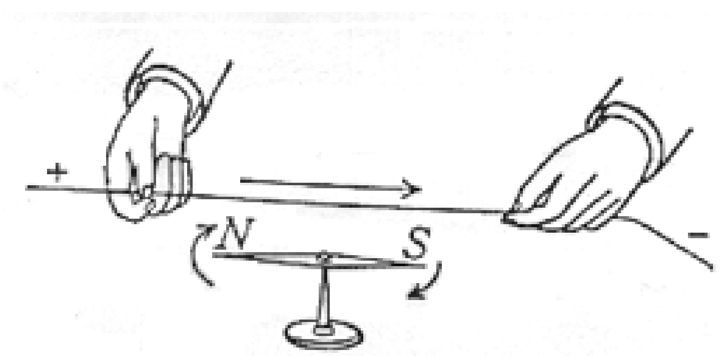
A “pure ”charge current made of two counter-propagating currents of the same amplitude but opposite charges:
The charge density is neutral everywhere, any effect?

A point charge at rest can not “see” a pure charge current (for it does not break the T-symmetry).

But a moving charge does (it is of the same symmetry-breaking type as the current).

So we have the Ampere effect (current-current coupling) and the Orsted effect (magnet is a small current loop)





What would be the probe of a pure spin current?

It should be a current of the same symmetry breaking type (in jargon: of the same tensor type).

An obvious solution is to use another spin current.

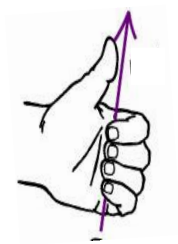
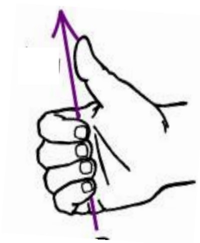
But we don't want to use another spin current. (Otherwise, how to measure the probe?)

For a solution, we just need shed a little light.

Yes, we just need a little light

A photon has two polarization states.

Jones vector representation:

 $\Leftrightarrow |\downarrow\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$  $\Leftrightarrow |\uparrow\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

The photon polarization is a pseudo vector, the same as a spin.

A polarized light beam is a "photon spin current" (a pure one is the energy current is not counted).

In tensor formalism: $\square \equiv q\mathbf{I}\mathbf{z}$

$\mathbf{I}$: photon "spin" polarization

$\mathbf{z}$: light beam direction

$\mathbf{q}$: light wavevector

Symmetry Analysis

Suppose the system has P & T

	H_{eff}	$\mathbf{S}$	$\mathcal{J}$	I_x	I_y	I_z	$\mathbf{q}$
P	+	+	−	+	+	+	−
T	+	−	+	+	+	−	−

Coupling in the 0th order of q:

$H_{\text{eff}}^{(0)} \propto I_z \mathbf{z} \cdot \mathbf{S},$ i.e., Faraday rotation in magnetooptics

Coupling in the 1st order of q:

$H_{\text{eff}}^{(1)} \propto I_z \mathbf{q}\mathbf{z} : \mathcal{J},$ i.e., circular birefringence w/o T-breaking

Symmetry Analysis (II)

Consider a specific form of spin current

$$\mathcal{J} \propto J_x \mathbf{XZ} + J_y \mathbf{YZ} + J_z \mathbf{ZZ} = \mathbf{JZ}$$

Under reflection about z-Z plane:

$$q \xrightarrow{\text{ref. about } \mathbf{z}\text{-}\mathbf{Z}} q, \qquad \mathbf{J}_{||} \xrightarrow{\text{ref. about } \mathbf{z}\text{-}\mathbf{Z}} -\mathbf{J}_{||},$$

$$I_z \xrightarrow{\text{ref. about } \mathbf{z}\text{-}\mathbf{Z}} -I_z \qquad J_{\perp} \xrightarrow{\text{ref. about } \mathbf{z}\text{-}\mathbf{Z}} J_{\perp}$$

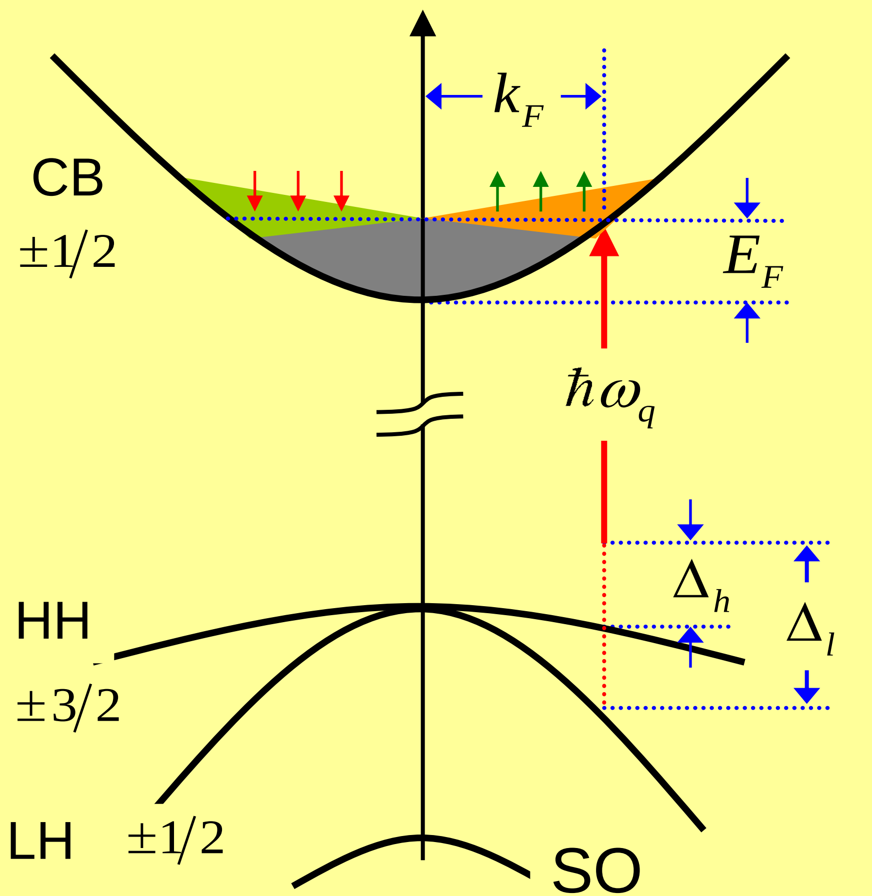
So: $H_{\text{eff}}^{(1)} = AqI_z J_Z + BqI_z J_Z = aqI_z J_Z + b\mathbf{z} \cdot \mathcal{J} \cdot \mathbf{z}$

Only two coupling constants left undetermined.

J. Wang, SN Ji, BF Zhu, & RBL (unpublished)

Microscopic model: Bulk III-V compound (like GaAs)

Spin current by a quasi-static non-equilibrium distribution slightly different from a Fermi surface.



1. Spin-orbital coupling needed for coupling light E-field and electron spin;
2. SO coupling in valence bands (relativity effect);
3. No Rashba effect in CB & Dresselhaus effect is negligible (spin splitting ~ 0.01 meV for doping ~10^{16} cm^{-3} in GaAs);
4. The light is tuned below Fermi surface (no real excitation);
5. Current-current coupling by virtual absorption & emission;
6. Virtual processes → phaseshift.

What are the physical effects?

Linear susceptibility:

$$\chi_{\sigma,\sigma'} + \chi^*_{\sigma',\sigma} = \frac{1}{\epsilon_0}\frac{\partial^2 \mathcal{H}_{\text{eff}}}{\partial F^*_\sigma \partial F_{\sigma'}}$$

Optical field of certain polarization

$$\mathcal{H}^{(1)}_{\text{eff}} = \zeta_2 q I_z \mathbf{z}\cdot\mathbb{J}\cdot\mathbf{z} + \zeta_3 q I_z J_Z$$

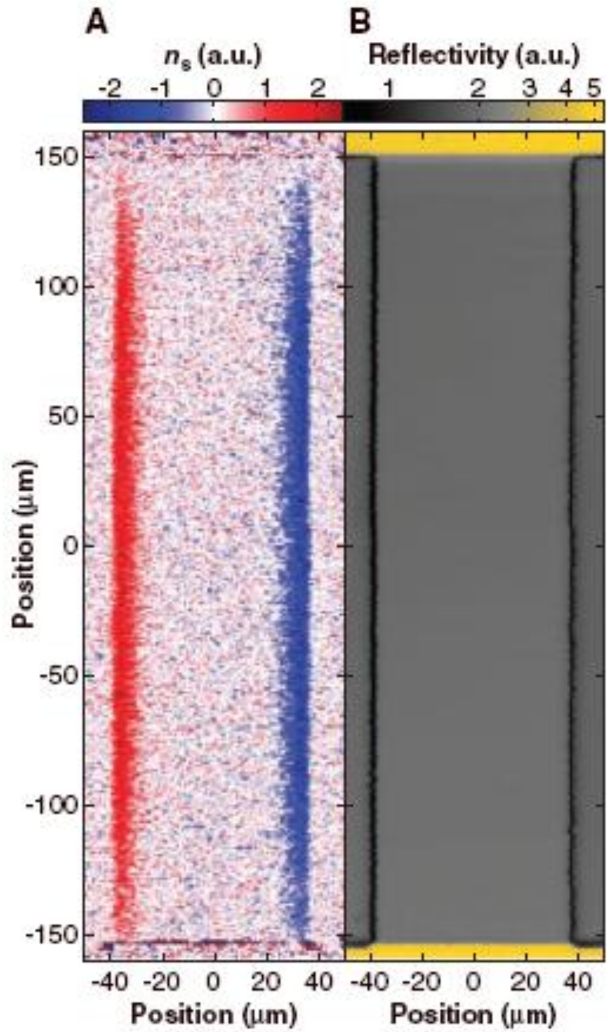
$$I_Z = F^*_+ F_+ - F^*_- F_-$$

Birefringence for circular polarizations

$$\chi_{++} = -\chi_{--} = \frac{q}{4\epsilon_0}\left(\zeta_2 \mathbf{z}\cdot\mathbb{J}\cdot\mathbf{z} + \zeta_3 J_Z\right)$$

Similar to the Faraday rotation in magneto-optics.
But no net magnetization here.

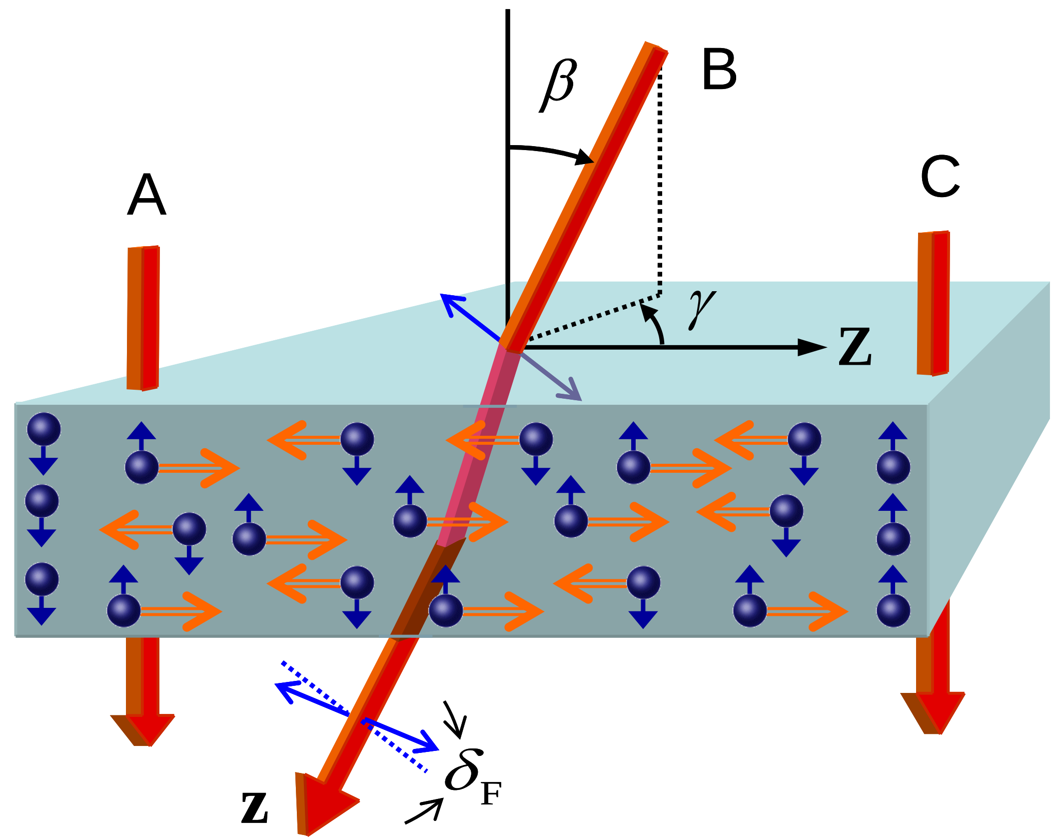
Why not seen before?



Normal incidence: Symmetry → no coupling

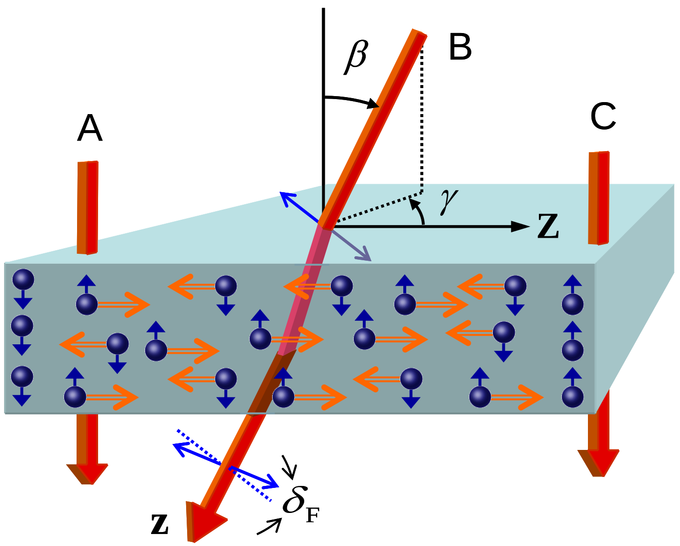
check reflection by surface plane

Solution: Observation by oblique light



Y. K. Kato et al, Science **306**, 1910 (04).

How big would be the effects?



The Faraday rotation angle

$$\theta_F \propto \frac{\cos\beta' \sin\beta' \cos\gamma}{|\cos\beta'|} = \pm\theta_{F,0} \sin\beta \sin\gamma$$

Sign flip at reflection.

For a spin current 20 (nA μm^{-2}).

Maximum values: $\theta_{F,0} \approx 0.4\ \mu\text{rad}$

reached when $\beta \to \pi/2$ and $\gamma \to 0$

J. Wang, B. F. Zhu, & RBL, Phys. Rev. Lett. **100**, 086603 (2008).

Linear optical effect depends on the small light wave vector q, and therefore is small

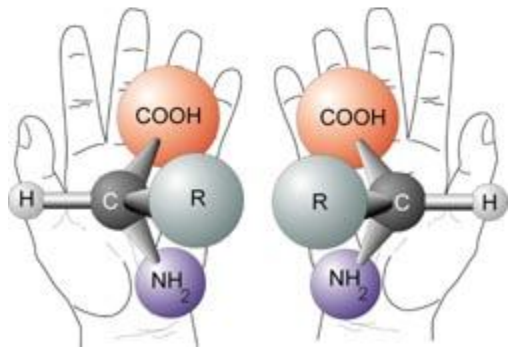
$$\theta_F^{(1)} \sim q$$

$\theta_{F,0} \approx 0.4\ \mu\text{rad}$ for a spin current 20 A/μm^{-2}

$$\mathbf{q}\cdot\mathbf{v} \Rightarrow \mathbf{E}\cdot\mathbf{V}\,?$$

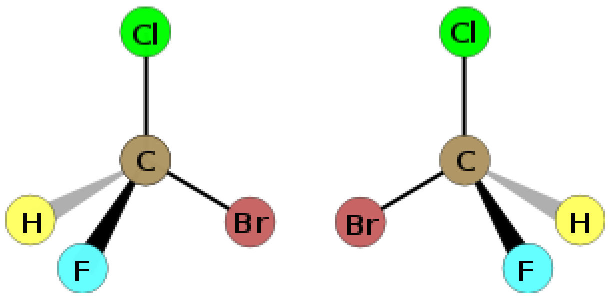
That means 2nd order nonlinear optics

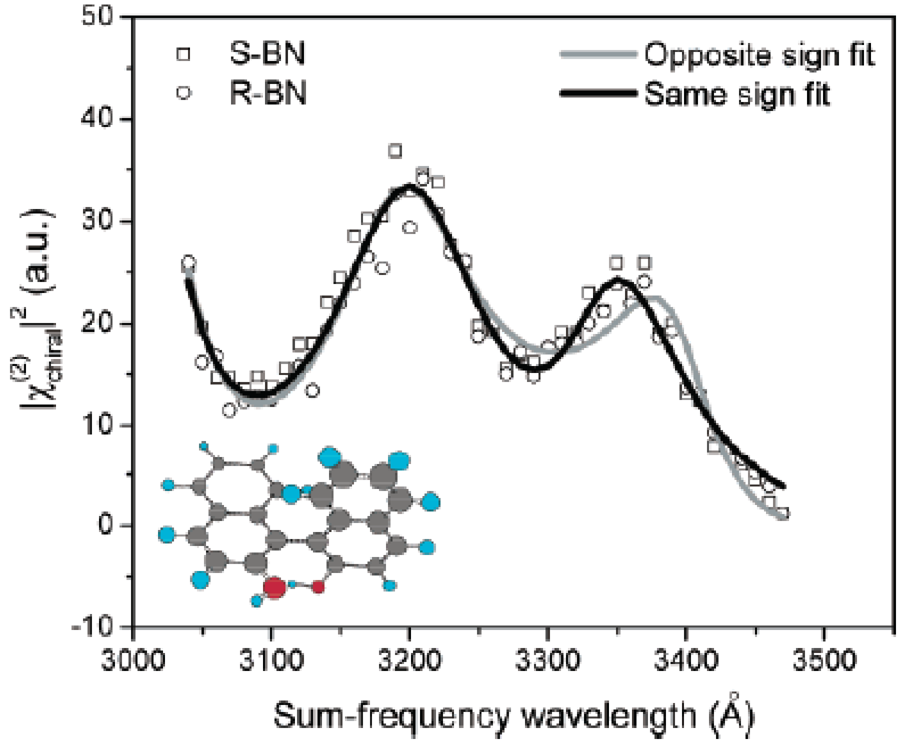
Chiral sum-frequency spectroscopy of chiral molecules



Shen YR et al, JACS 128, 8845 (06)

Toward chiral sum-frequency spectroscopy



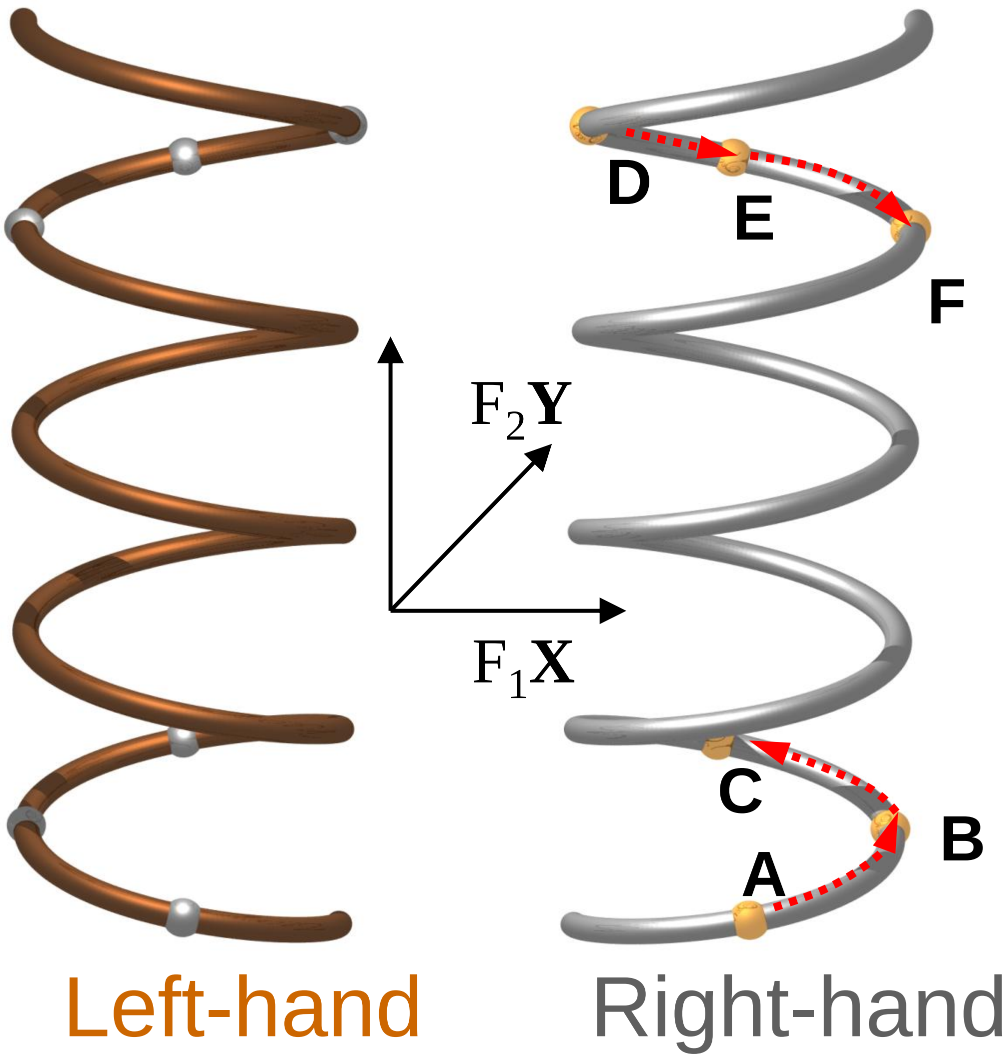


$$\chi^{(2)}_{XYZ} \neq 0$$

Istropic: $\chi^{(2)} = \left|\chi^{(2)}\right| \varepsilon_{ijk}$

In linear optics, only magnetic dipole contributes:
Signal depending on the small light wavevector q.

Chiral sum-frequency in chiral systems



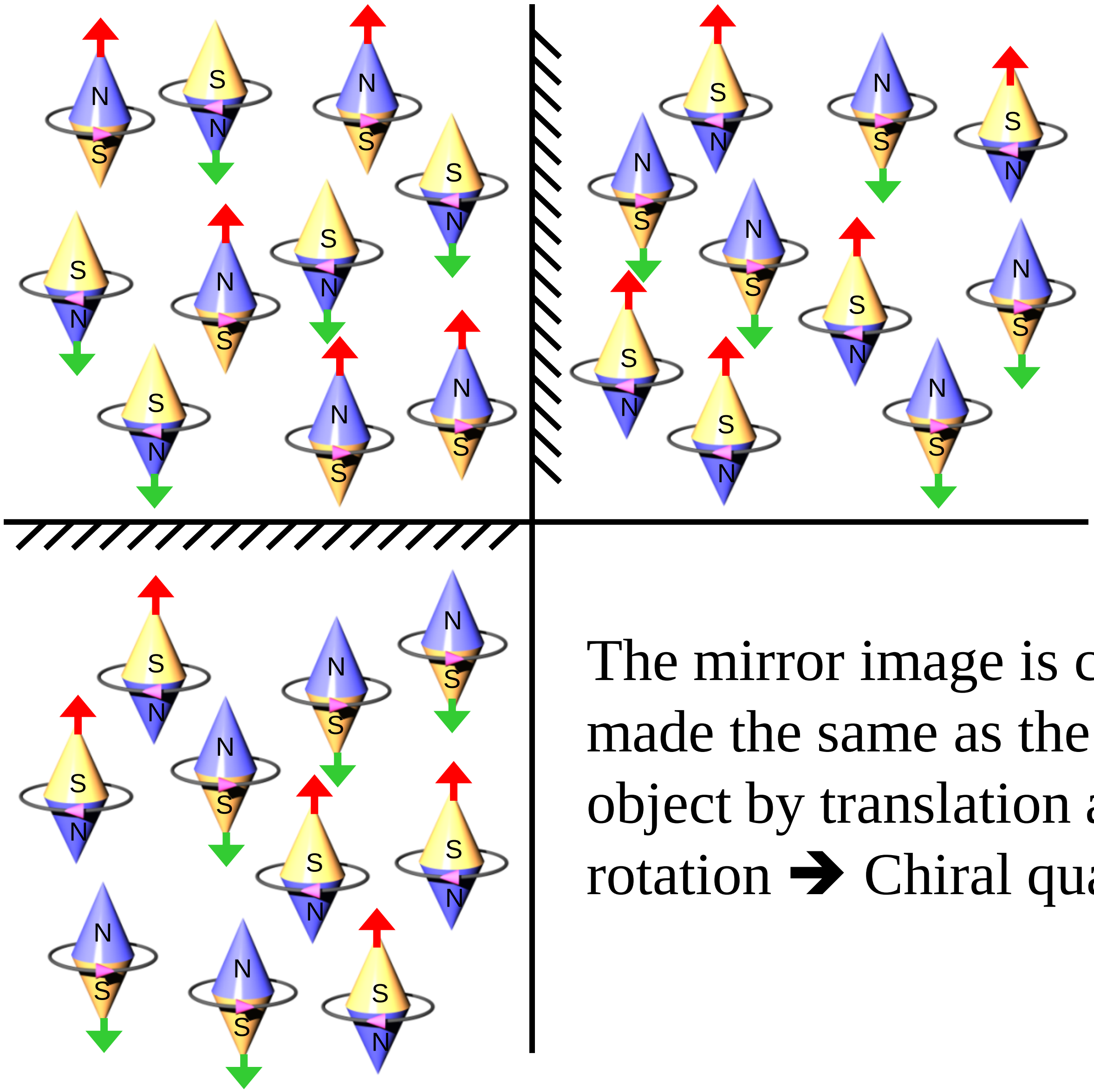
$$\left.\begin{array}{l} F_2\mathbf{Y}:\ \mathrm{D}\rightarrow E \\ F_1\mathbf{X}:\ \mathrm{E}\rightarrow F \end{array}\right\}:\ -r\mathbf{Z}$$

right-hand: $(\mathbf{Y},\mathbf{X},-\mathbf{Z})$

$$\left.\begin{array}{l} F_1\mathbf{X}:\ \mathrm{A}\rightarrow \mathrm{B} \\ F_2\mathbf{Y}:\ \mathrm{B}\rightarrow \mathrm{C} \end{array}\right\}:\ +r\mathbf{Z}$$

right-hand: $(\mathbf{X},\mathbf{Y},\mathbf{Z})$

Longitudinal spin current is chiral



The mirror image is cannot be made the same as the original object by translation and rotation ➔ Chiral quantity

General case: symmetry analysis

In general, a spin current breaks inversion symmetry,

$$\mathcal{J} = \mathbf{s}\mathbf{v} \rightarrow (\mathbf{s})(-\mathbf{v})$$

➔ nonzero 2nd-order nonlinear optical effect

$$\mathbf{P}(\omega_1 + \omega_2) = \chi^{(2)} : \mathbf{F}_1(\omega_1)\mathbf{F}_2(\omega_2)$$

Longitudinal part: $\mathcal{J} = J_Z \mathbf{ZZ}$

$$\chi_L^{(2)} = J_Z \left[\alpha_1(\mathbf{ZXY} - \mathbf{ZYX}) + \alpha_2(\mathbf{YZX} - \mathbf{XZY}) + \alpha_3(\mathbf{XYZ} - \mathbf{YXZ})\right]$$

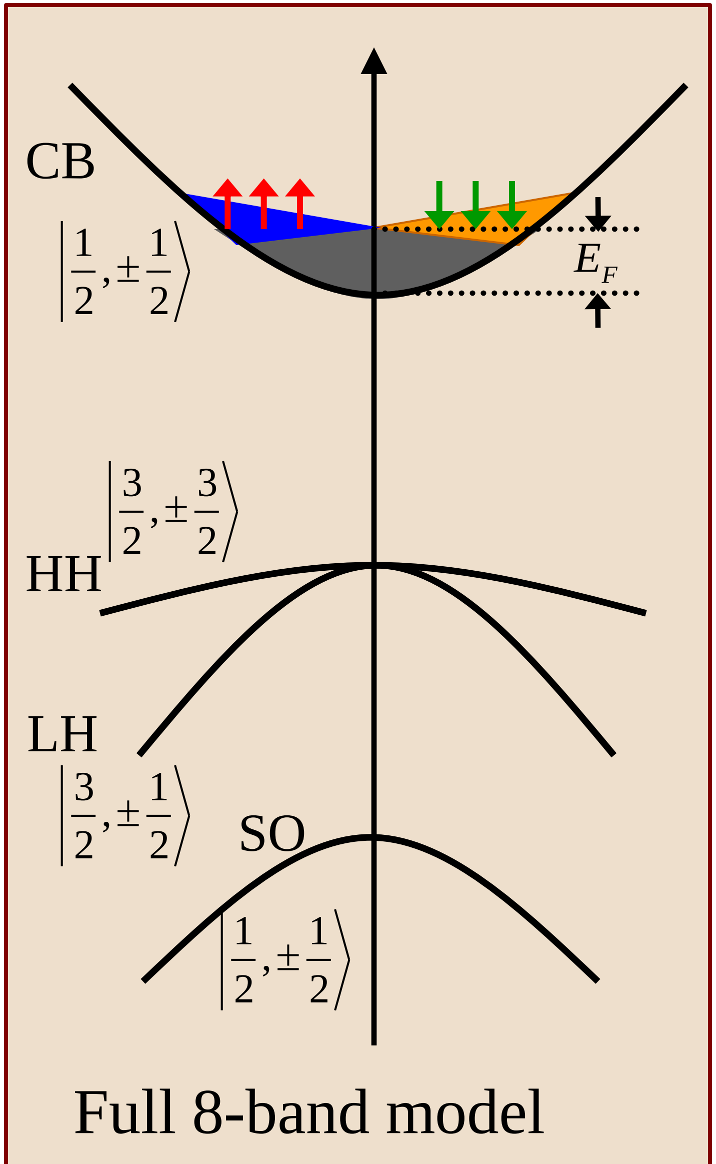
Only 3 free parameters to be determined (all chiral terms).

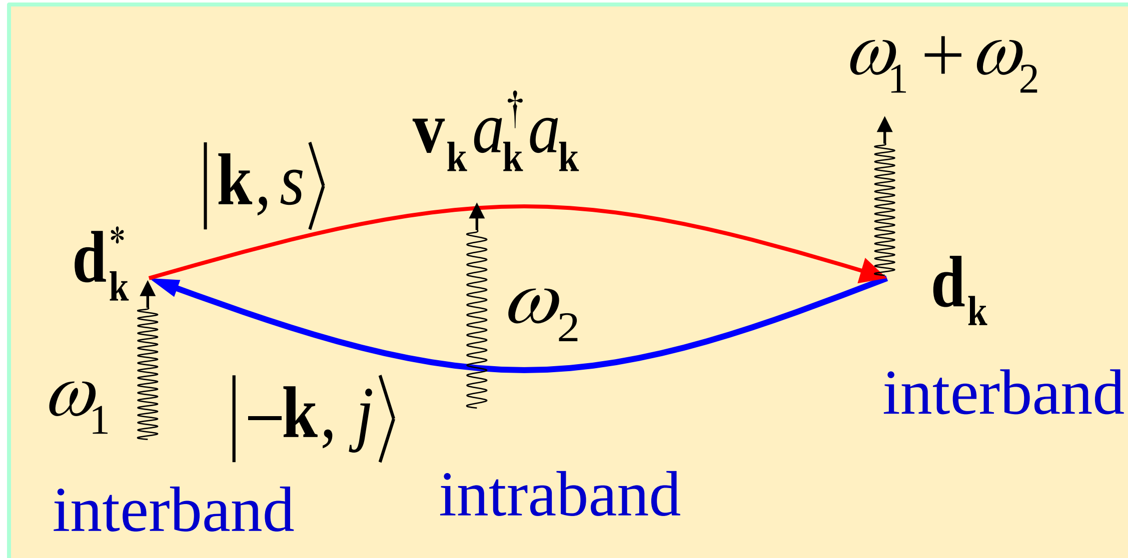
Transverse part: $\mathcal{J} = J_X \mathbf{XZ}$

$$\chi_T^{(2)} = J_X \left[x_1\mathbf{XXY} + x_2\mathbf{XYX} + x_3\mathbf{YXX} + z_1\mathbf{ZZY} + z_2\mathbf{ZYZ} + z_3\mathbf{YZZ} + y\mathbf{YYY}\right],$$

Seven free parameters to be determined.

Standard (though lengthy) perturbation method





$$\propto \mathbf{E}^* \cdot \mathbf{d}_\mathbf{k} \mathbf{d}_\mathbf{k}^* \cdot \mathbf{E}_1 \mathbf{v}_\mathbf{k} \cdot \mathbf{E}_2$$

Spin polarization

velocity

Microscopic mechanism in short

Consider one electron with spin **S** and velocity **V**.

Spin current due to this electron is **SV**.

$$\mathbf{P} \propto \mathbf{F}_2 \times \mathbf{S}\mathbf{V} \cdot \mathbf{F}_1$$

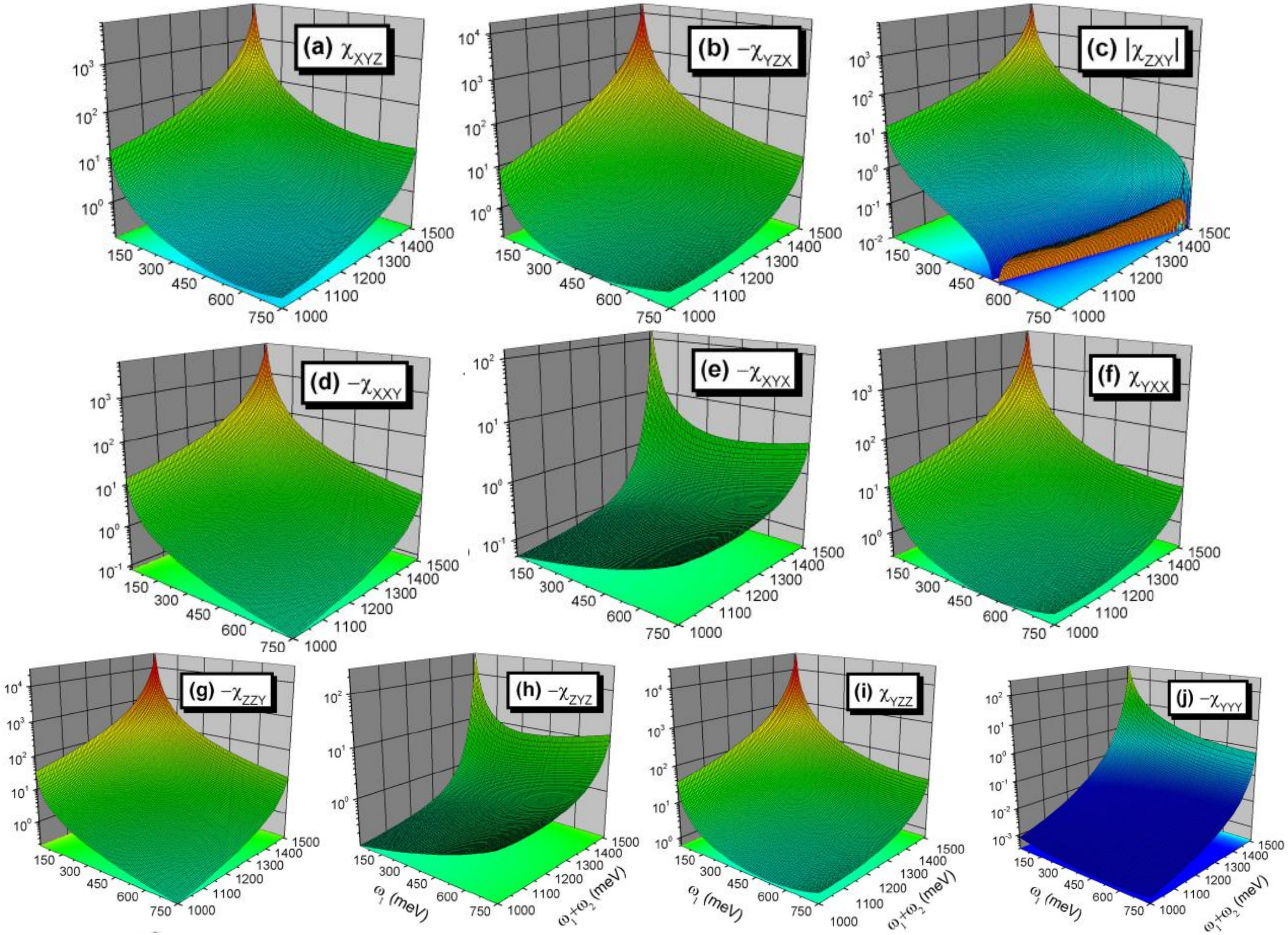
Faraday rotation

Spin current

Intraband acceleration

$$\chi^{(2)} = \xi \varepsilon_{ijk} \mathbf{e}_i \mathbf{e}_j \mathbf{e}_k \cdot \mathcal{J}$$

Microscopically calculated sum-frequency spectra



How big could be the effect?

1. Proportional to current amplitude
2. Depending on detuning

inputs @ 800 nm and 30μm wavelenths

(i.e., double resonance condition)

10 nA/μm^{-2} spin current

GaAs

$$\chi^{(2)} \sim 10^{-6}\ \text{esu} \sim 3\times 10^{-9}\ \text{cm}/V$$

J. Wang, B. F. Zhu, & RBL, arXiv 1001.1053 (2010).

Summary

1. Spin current has peculiar symmetry breaking: It can be detected by a probe breaking the same symmetry
2. Linear optics: Circular birefringence without breaking T (but depending on small *q*)
3. Nonlinear optics: Strong chiral & normal sum-frequency susceptibility
4. Optical spectroscopy as a toolbox for studying spintronics & topological insulators