# Magneto-electric Conversion of Optical Energy to Electricity

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**Introduction:**

- *Objective: new capabilities for advanced Air Force missions*
- *Background on solar cells & photovoltaic technology*
- *Conversion of light to electricity without semiconductors*
- *a simple classical picture*

**Results to date on Transverse Magnetic Effects:**

- *an exact quantum picture to clarify key dependences*
- *materials roadmap:  organic, inorganic & hybrid materials*

**Applications of Intense Dynamic Magneto-Optics:**

- *M-E conversion of coherent laser beams to electricity*
- *M-E solar power without heat generation ($\eta$~1)?*
- *programmable magnetic field generation without coils (B>10 Tesla)?*

*AFOSR Program Review* *Arlington, Feb. 11-15, 2013*

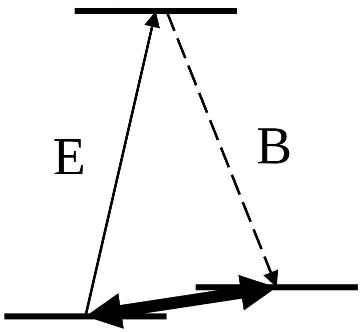
# Future Capabilities in Extreme Environments

## Power Beaming:

- Sustained flight for unmanned Aerial Vehicles (UAV)
- Power transmission without transmission lines
- Remote power transfer in extreme environments (space)
- Remote energizing of high power robotic or disabled missions
- High power, cool electrical generation in vacuum

## Efficient Solar Converters:

- High power solar reactors on the ground and in space
- High efficiency, without heat generation (theoretical $\eta$>85%)
- Unconverted light is simply transmitted – could be captured by photovoltaics in hybrid systems for $\eta$ ~100%




Electric Dipole

# What is Needed to Achieve these New (Optical) Capabilities?

- **Fundamental Understanding:**

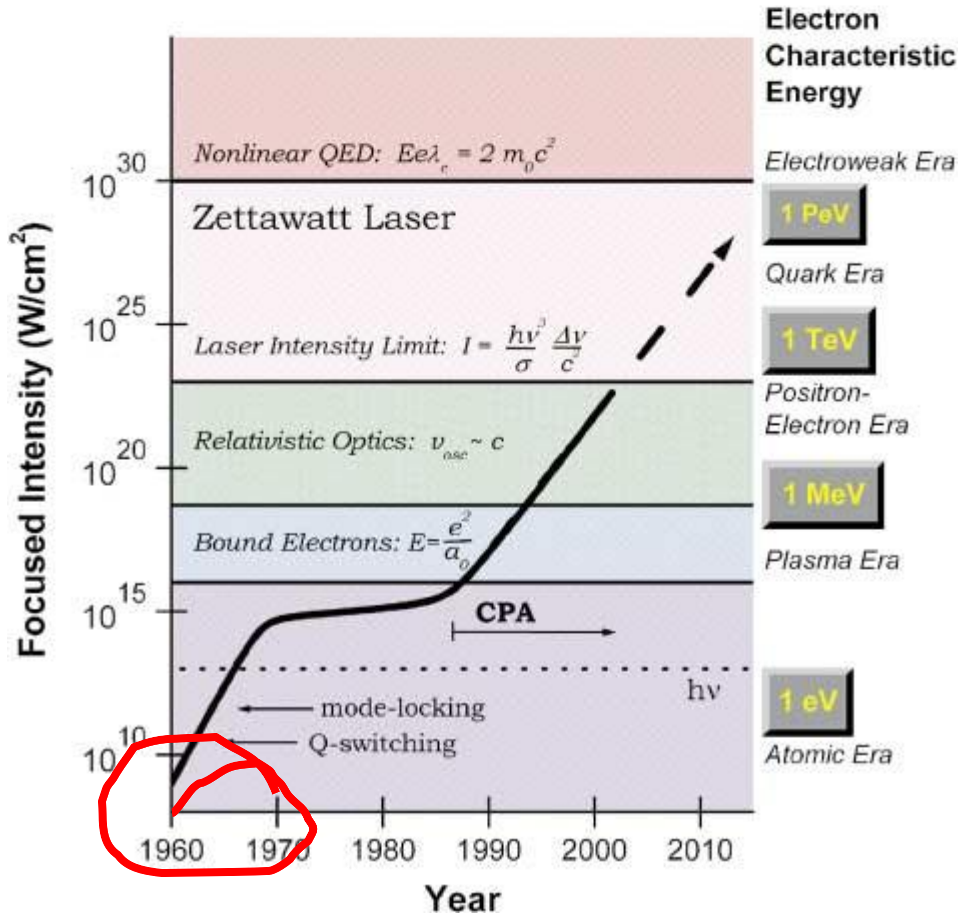
  Magneto-electric conversion of light energy directly to electricity (new physics of "optical capacitors")

- **New, optically magnetizable materials:**

  Organic ⟷ Inorganic ⟷ Transparent Ceramics

  capable of withstanding intense light.

# What optical intensities are required?




*Ref: T. Tajima and G. Mourou, Phys. Rev. Sp. Topics 5, 031310 (2002)*

# Traditionally, Induced Magneto-electric Effects are *expected* to be weak & slow

Why? Compare all-electric response: $\chi \propto EE$
with magneto-electric response: $\chi \propto EB$

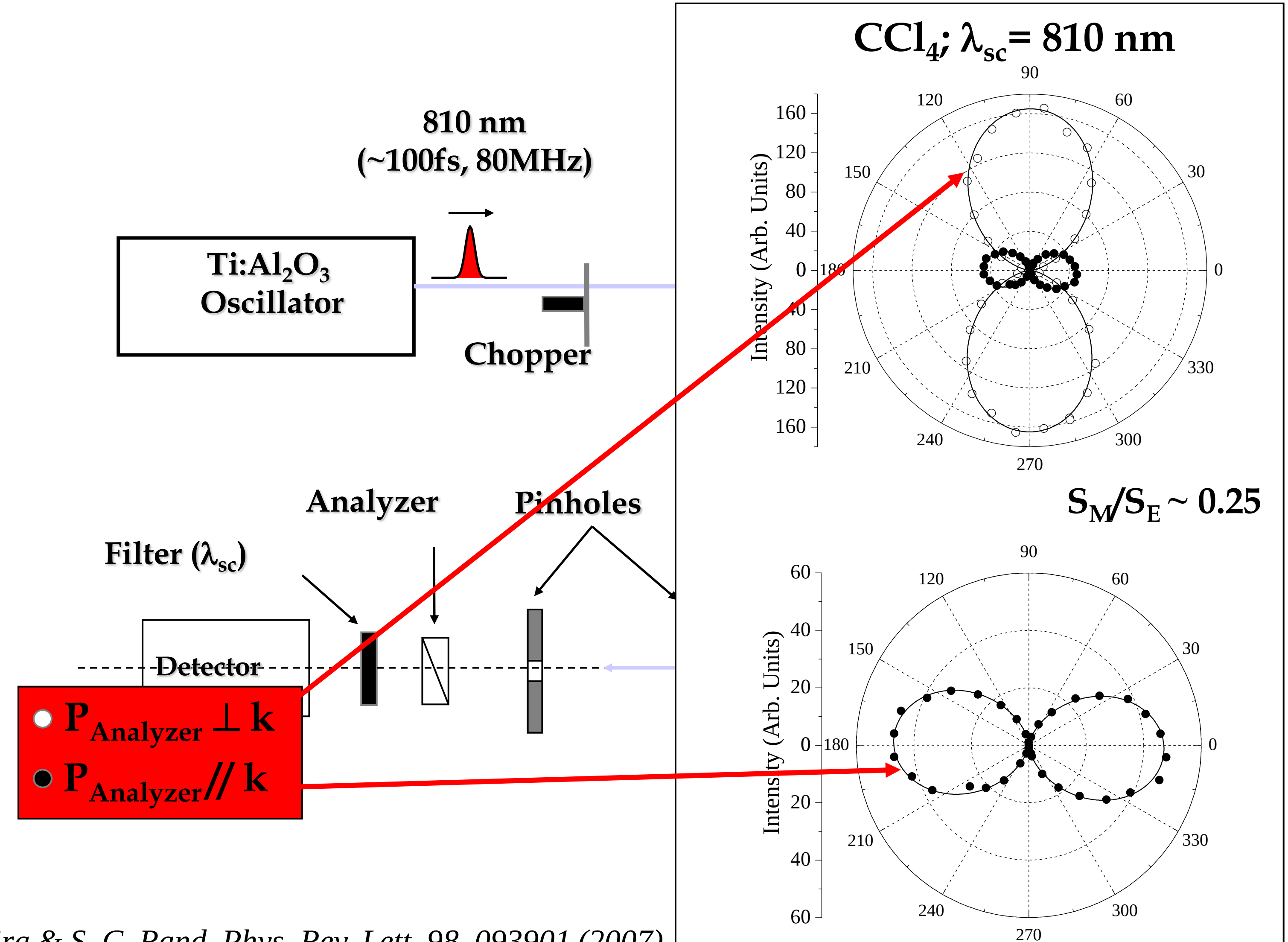
(a) Optical magnetic field of a plane wave is inherently smaller than the optical electric field:

$$B_{light} = E_{light} / c$$

(b) Magnetic dipoles induced by light are much smaller than electric dipoles (according to the multipole expansion).

# Experiments on Dipole Scattering

**(at non-relativistic intensities: I~10⁸ W/cm² <<10¹⁸ W/cm²)**




*S. L. Oliveira & S. C. Rand, Phys. Rev. Lett. 98, 093901 (2007)*

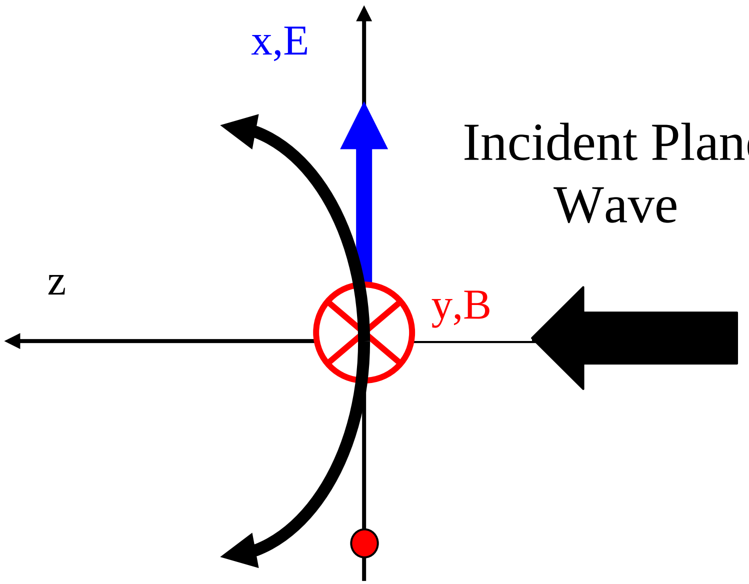
# Classical Model of Bound Electron Motion

Magneto-electric Rectification (charge separation)

$$m\frac{\partial^2 \bar{r}}{\partial t^2} = \bar{F}$$

$$\frac{\partial^2 x(t)}{\partial t^2} + \gamma_1 \frac{\partial x(t)}{\partial t} + \omega_1^2 x(t) = -\frac{eE(t)}{m_e} + \frac{eB(t)}{m_e}\frac{\partial z(t)}{\partial t}$$

$$\frac{\partial^2 z(t)}{\partial t^2} + \gamma_2 \frac{\partial z(t)}{\partial t} + \omega_2^2 z(t) = -\frac{eB(t)}{m_e}\frac{\partial x(t)}{\partial t}$$




$$z(t) = \frac{-\omega^2 q^2 E_0 B_0}{2m^2 \omega_2^2 \sqrt{(\omega_1^2 - \omega^2)^2 + \gamma_1^2 \omega^2}} \sin(\phi_0) + \frac{\omega^2 q^2 E_0 B_0}{2m^2 \sqrt{[\omega_2^2 - (2\omega^2)]^2 + \gamma_2^2 (2\omega)^2}\sqrt{(\omega_1^2 - \omega^2)^2 + \gamma_1^2 \omega^2}} \sin(2\omega t + \phi_0 - \phi_1)$$

where $\phi_1 \equiv \tan^{-1}(-\gamma_2 2\omega / [\omega_2^2 - (2\omega)^2])$ and $\omega_2 \approx 0$ .

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$$m\frac{\partial^2 \bar{r}}{\partial t^2} = \bar{F}$$

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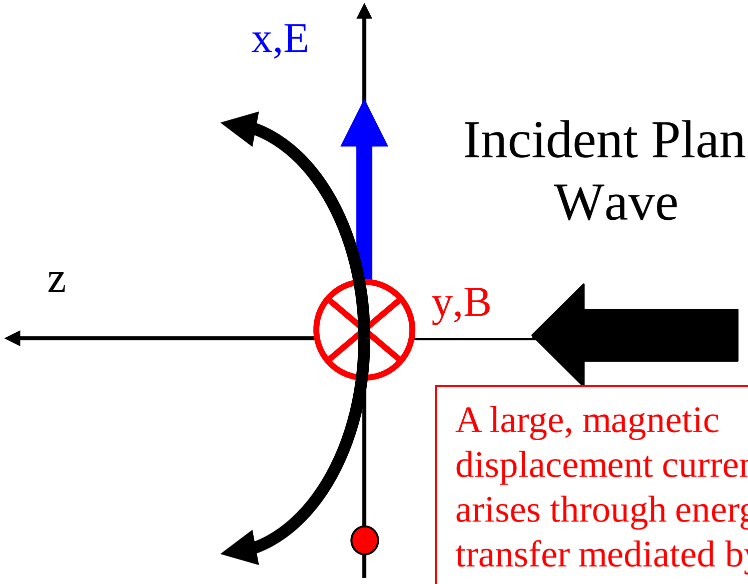
$$\frac{\partial^2 z(t)}{\partial t^2} + \gamma_2 \frac{\partial z(t)}{\partial t} + \omega_2^2 z(t) = -\frac{eB(t)}{m_e}\frac{\partial x(t)}{\partial t}$$



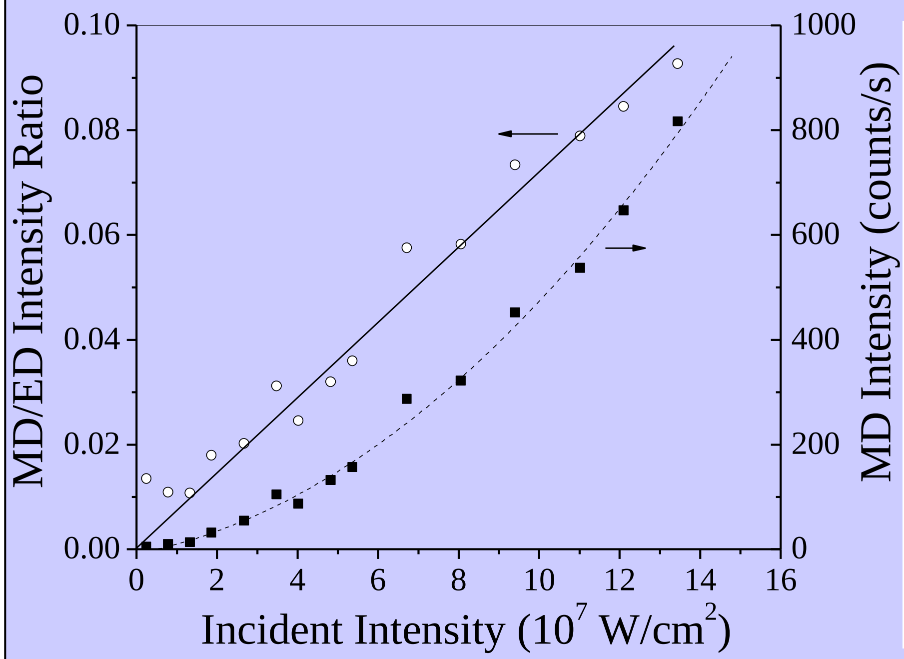

A large, magnetic displacement current arises through energy transfer mediated by parametric resonance between motions driven by E and B

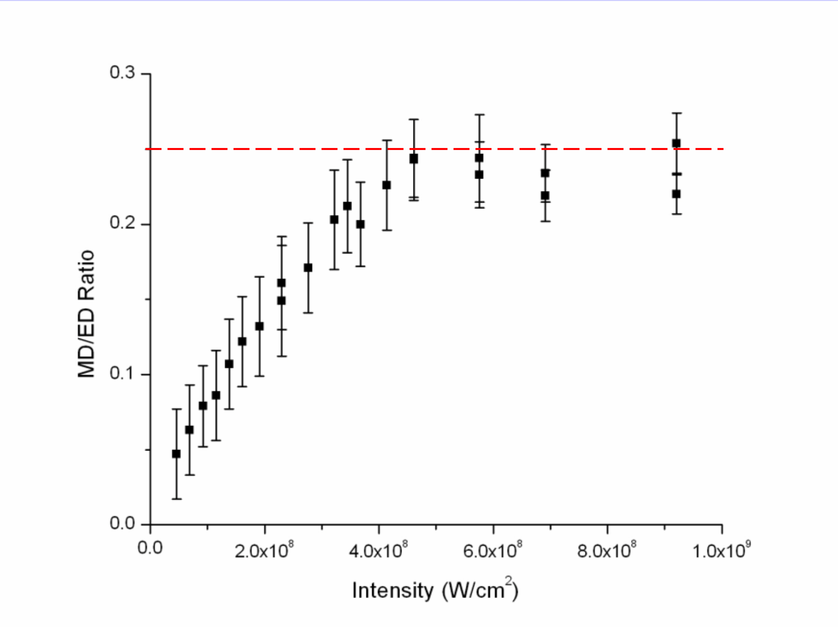
$$z(t) = \frac{-\omega^2 q^2 E_0 B_0}{2m^2\omega_2^2\sqrt{(\omega_1^2-\omega^2)^2+\gamma_1^2\omega^2}}\sin(\phi_0) +$$

$$\frac{\omega^2 q^2 E_0 B_0}{2m^2\sqrt{[\omega_2^2-(2\omega^2)]^2+\gamma_2^2(2\omega)^2}\sqrt{(\omega_1^2-\omega^2)^2+\gamma_1^2\omega^2}}\sin(2\omega t+\phi_0-\phi_1)$$

where $\phi_1 \equiv \tan^{-1}(-\gamma_2 2\omega/[\omega_2^2-(2\omega)^2])$ and $\omega_2 \approx 0$ .

# Intensity Dependence & Saturation of Magnetic Dipole Scattering

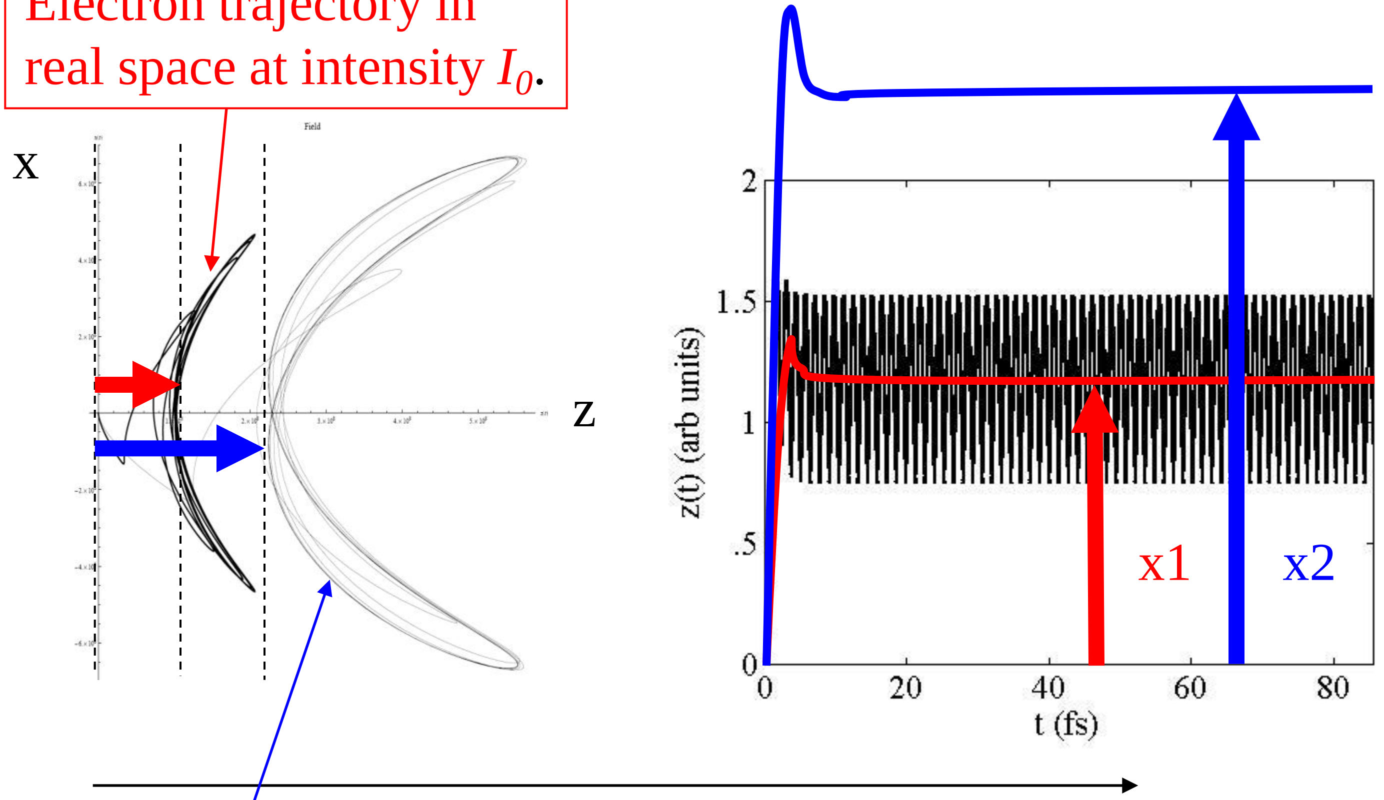



*Scattering data from a representative centro-symmetric scattering medium ($CCl_4$).*

# The "Optical Capacitor“ Concept

Electron trajectory in real space at intensity $I_0$.



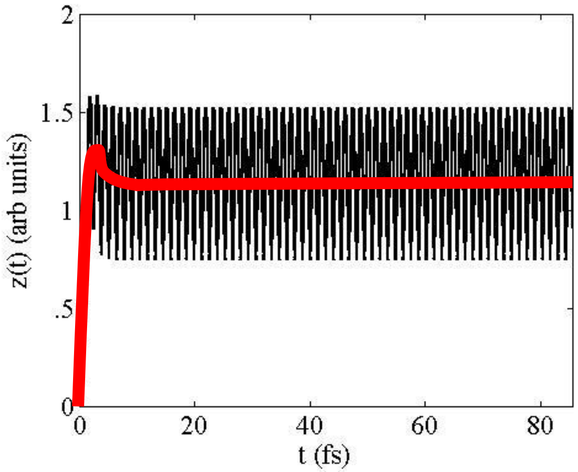

*Direction of light propagation*

Electron trajectory in real space at intensity $2I_0$.

# Charging the "Optical Capacitor" with Light:

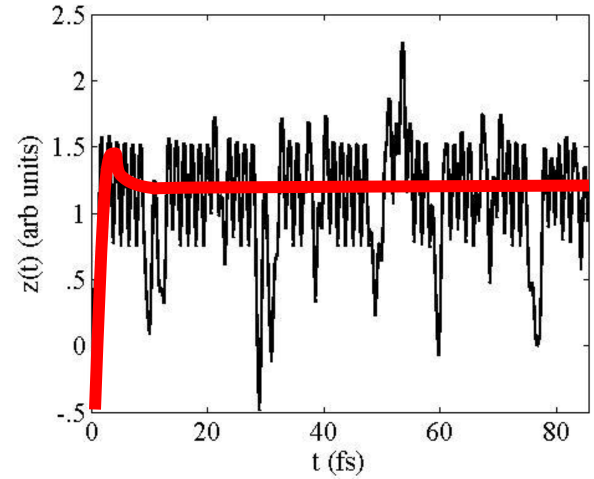
## Coherent vs. Incoherent Light

Coherent Light




$$\tau_c = \infty$$

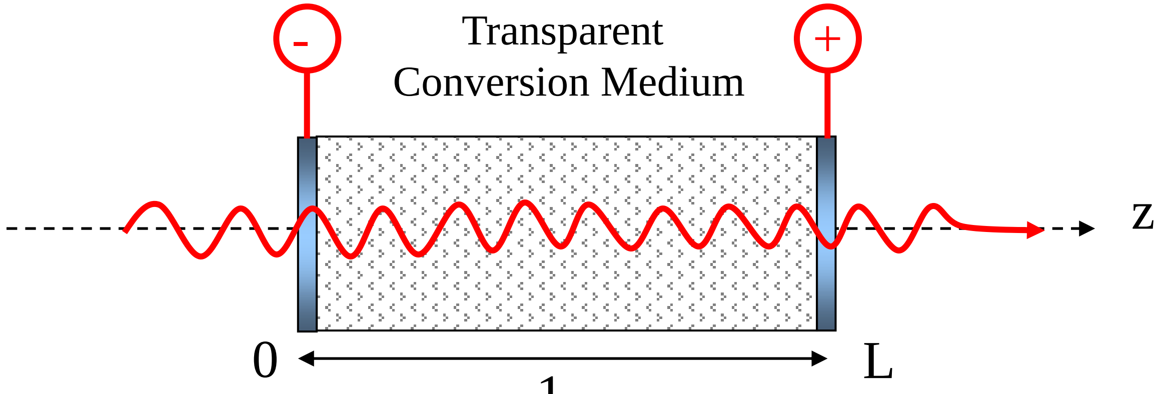
Incoherent Light
(randomized phase & polarization)




$$\tau_c = 3 \quad fs$$


*Ref: W.M. Fisher and S.C. Rand, "Optically-induced charge separation and THz emission in unbiased dielectrics", J. Appl. Phys. 109, 064903(2011).*

# Extractable energy of "Optical Capacitors"




$$U = \frac{1}{2} C V^2$$

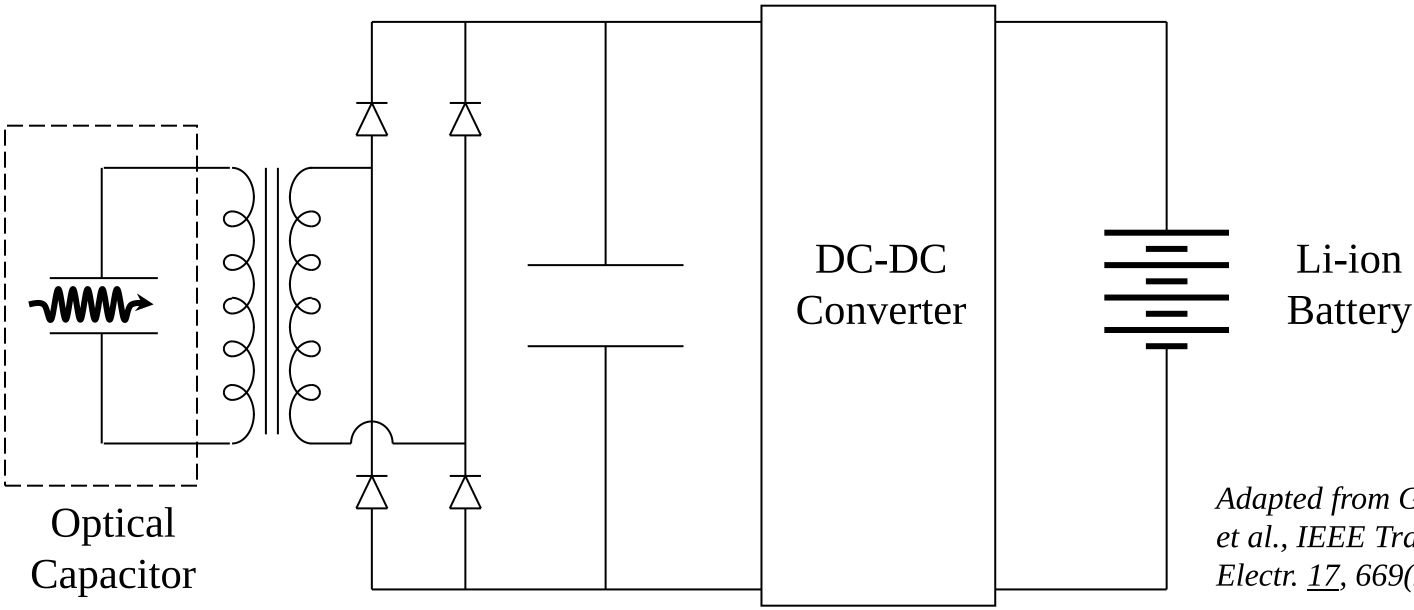
$$V = \frac{Q}{C} = \frac{\sigma_s A}{\varepsilon A / L} = \frac{P^{(m)} L}{\varepsilon} = \frac{-\frac{1}{2}\chi^{(e)} E L}{\varepsilon / \varepsilon_0} = -\frac{(\varepsilon_r - 1) E L}{2\varepsilon_r}$$

For an extraction rate of $\Omega$ and a beam area of $A = \pi\omega^2$, the available output power is:

$$Power = \frac{\varepsilon_0 \pi \omega_0^2 L}{4\varepsilon_r} (\varepsilon_r - 1)^2 \eta_0 \Omega I$$

*Ref: W.M. Fisher and S.C. Rand, "Optically-induced charge separation and THz emission in unbiased dielectrics", J. Appl. Phys. 109, 064903(2011).*

# Energy Conversion & Storage




*Adapted from G.K. Ottman et al., IEEE Trans. Power Electr. 17, 669(2002).*

Efficiency Estimate for Beam Conversion:

**$P_{in}$= 10 kW**; fiber length $L$=10 m & core radius $\omega_0$=70.5 $\mu$m

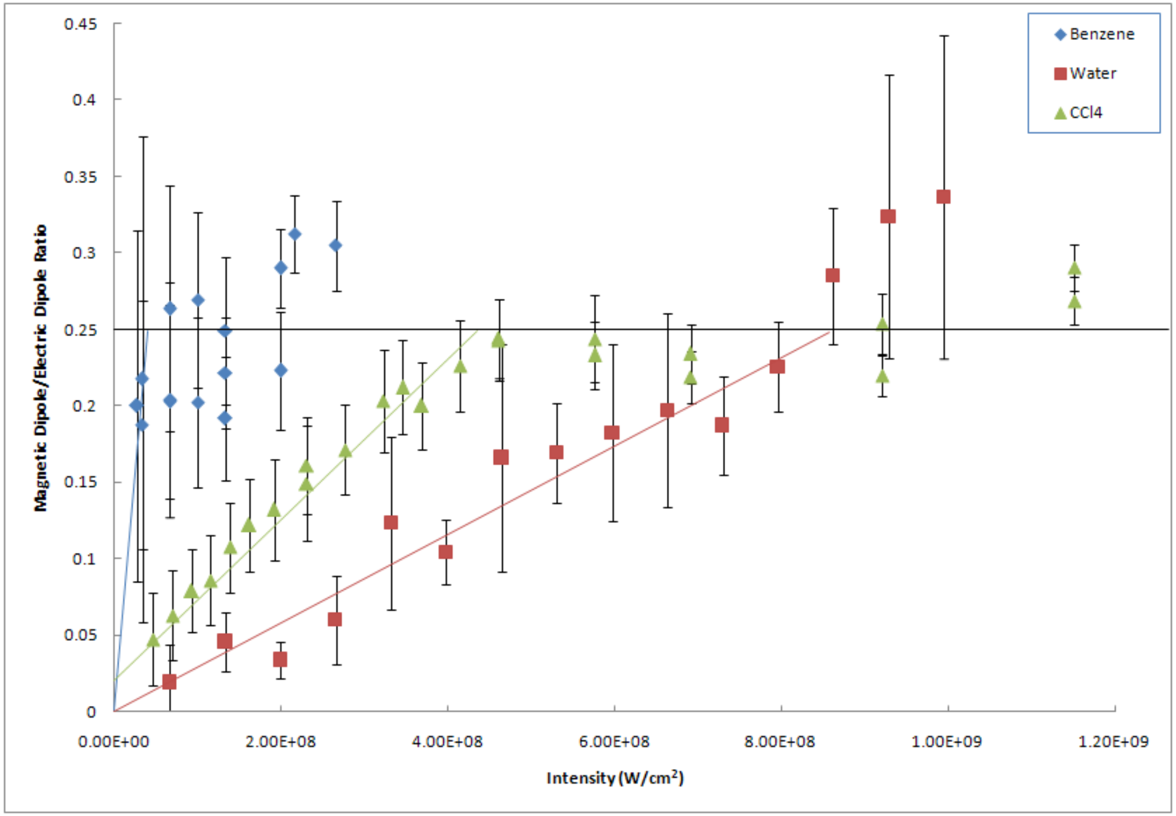
This yields:

**$P_{out}$=2.576 kW**

Thus conversion efficiency is 25.6% at extraction rate Ω=25 MHz in the undepleted pump limit. *(From W. Fisher and S.C. Rand, JAP 109, 064903(2011)).*

# Different Materials

## Exhibit Different Magneto-electric Susceptibility




Benzene

$CCl_4$

$H_2O$

There are 2 regimes:

(a) Low intensity

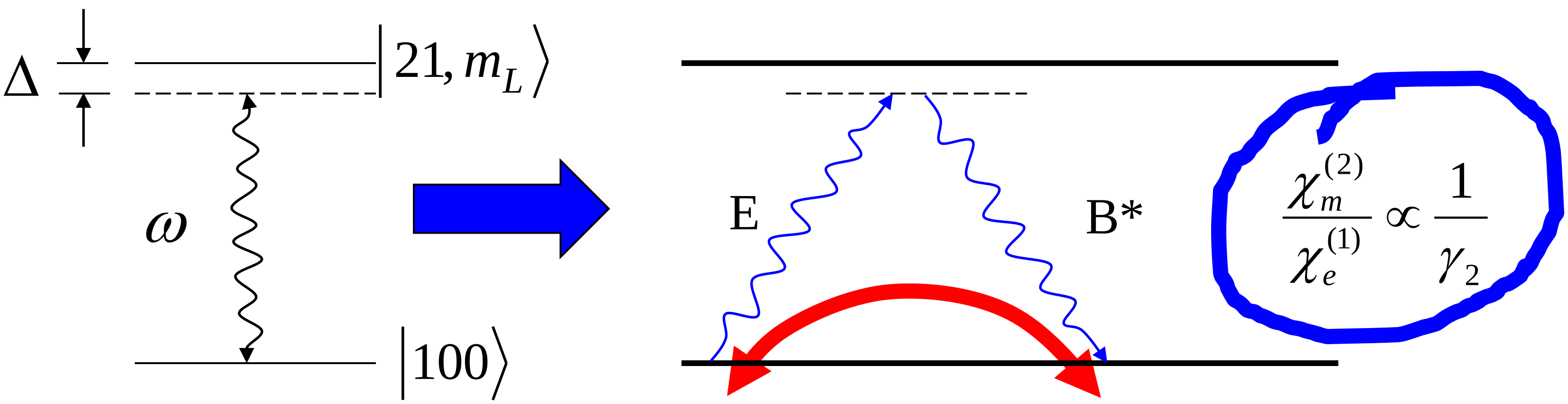
$$\frac{I_{MD}}{I_{ED}} \propto I_{inc}$$

(b) High intensity (saturated)

$$\frac{I_{MD}}{I_{ED}} = 0.25$$

# New Result: Exact Quantum Theory Highlights Material Parameter Needs

States mixed by BOTH *E* and *B*:




Resonantly-driven static dipole forms despite inversion symmetry! (Dynamic symmetry-breaking)

Rectification: $P(0) = e\langle 100|r|210\rangle \neq 0$

# Current (Initial) Materials Studies:
# Systematic Variations in Electron Delocalization

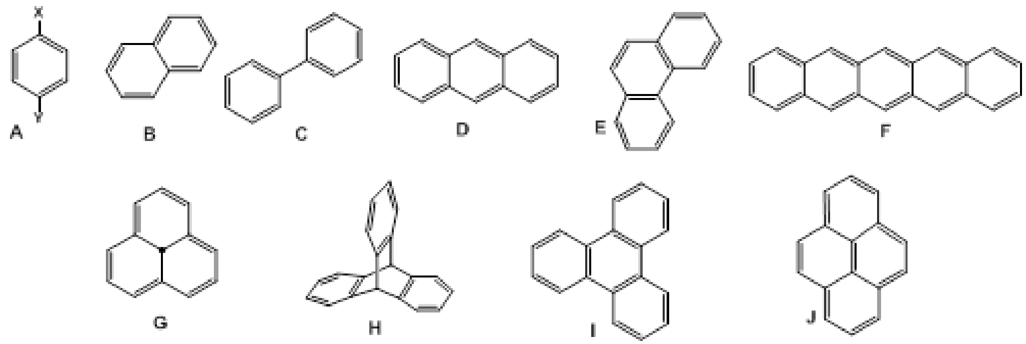
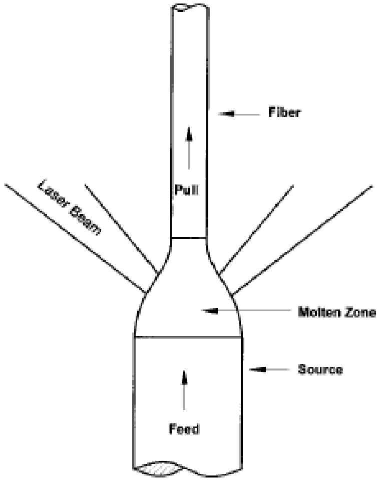
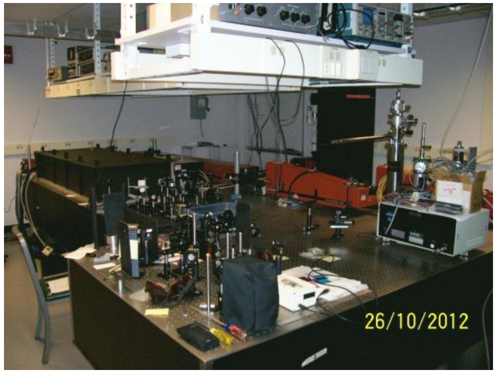


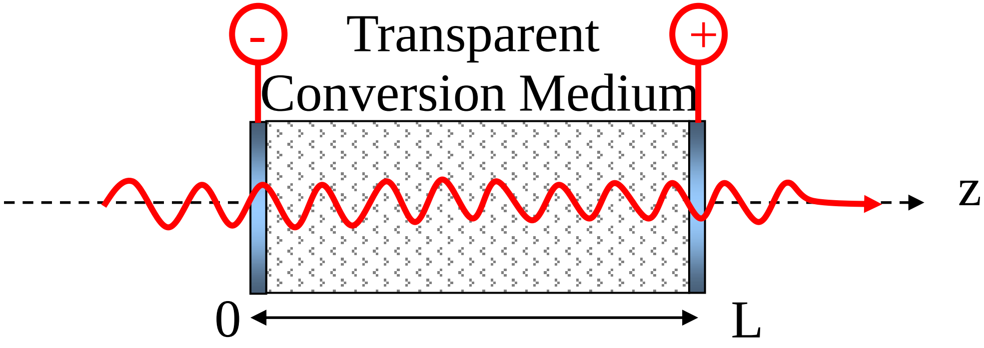

Chart 1. Exploring π-Electron Structure Effects. X, Y = Electron-Withdrawing/Donating Substituents; Those with High Z or Altered Mass




Experiments in solids:
- sapphire fibers
- scattering in silica



# Prospects for Optical Beam & Solar Conversion

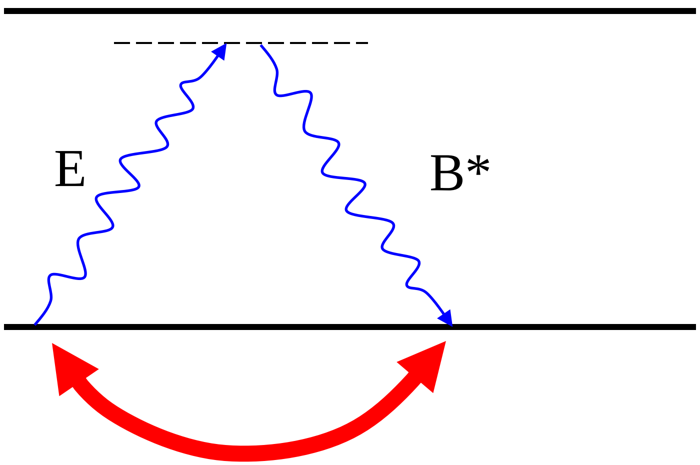



Coherent light from lasers is easily directed & focused

Electric conversion of sunlight to electricity will require transparent insulators that are effective at the intensities achievable with f#1 concentrators ($I \sim 10^8$ W/m$^2$)

# Unique Advantages of this Approach:

1. Light is not absorbed (atoms remain in the ground state). Thus unlike solar cells, no heating takes place !
2. Charge separation does not depend much on wavelength!




$$P(0) = e\langle 100 | r | 210 \rangle \neq 0$$

# SUMMARY

- New-start Program on Magneto-electric Energy Conversion:
  Maintenance of technological aerospace dominance through research on magnetic charge separation for power conversion (relativistic optics at non-relativistic intensities)

- Unanticipated Technological Capabilities via Magneto-optics:
  - Generation of large (oscillatory) magnetic fields (>10Tesla)
  - Impulsive generation of THz radiation in unbiased dielectrics
  - Magneto-electric conversion of electromagnetic beams to electricity
  - Magneto-electric conversion of incoherent sunlight to electricity with negligible generation of waste heat (*$\eta$>85%?)*

- The Materials Challenge:
  For extreme environments, and high optical intensities, robust nonlinear materials will be needed that combine exceptional thermal and chemical properties (minimal rotational damping). Transparent ceramics, hybrids….

Sam Oliveira, Cid De Araujo, L. Acioli, Gomes Anderson, Leonardo Menezes, Liz Cloos, Alex Fisher, William Fisher