# Thrust 1
# Project 1.1: Electro-optic Materials and Devices

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Arizona's First University.

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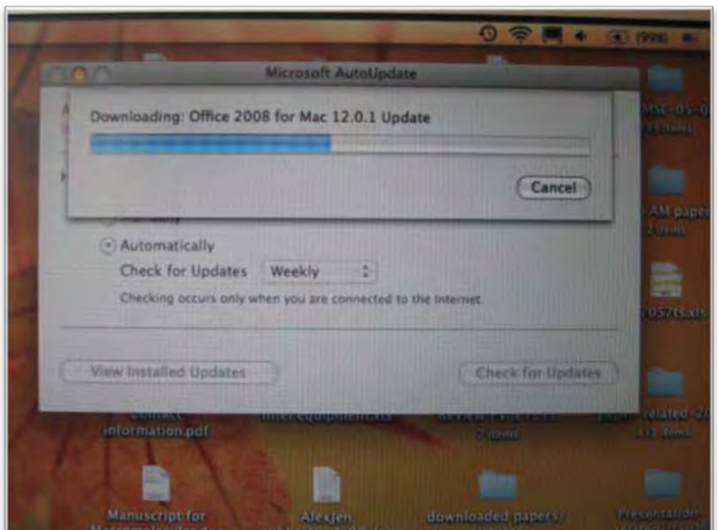
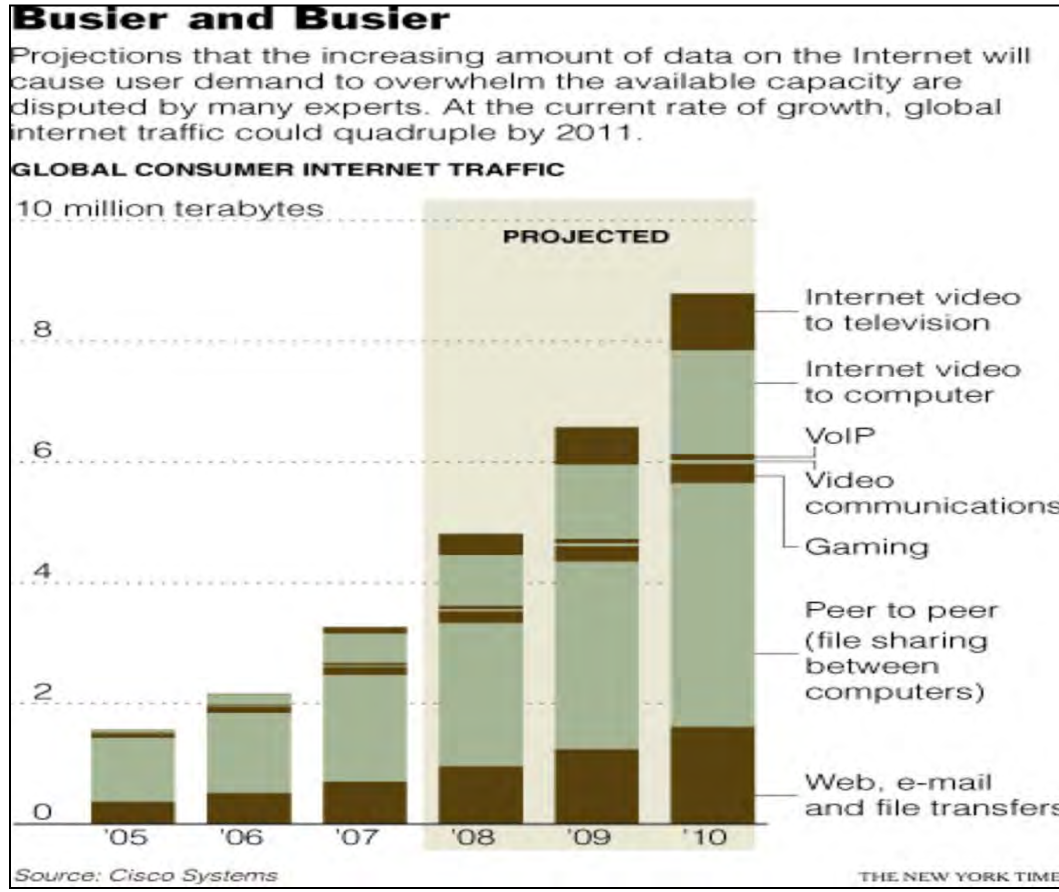
# How to Address the Challenges of Quadruple Rate Growth of Global Internet Traffic?

*Have you been frustrated by the experience of waiting for the slowly moving blue bar?*



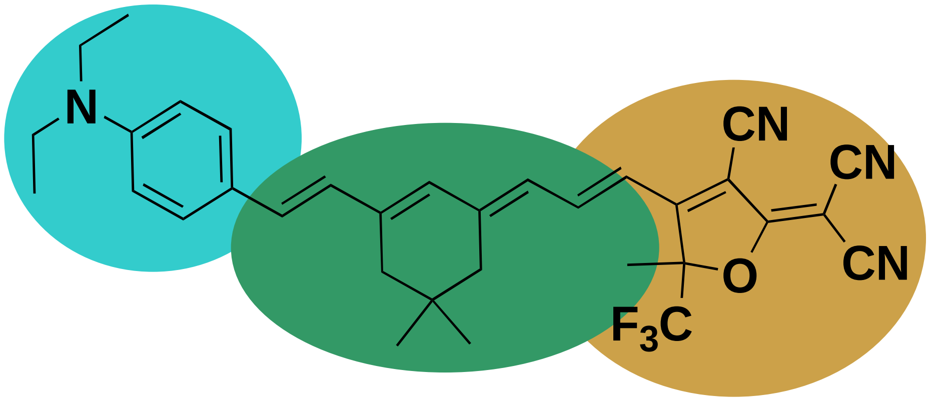

*It took me 20 min to download a 120 MB file using DSL @ home*

*The video site YouTube was estimated to consume as much bandwidth as entire Internet did in 2000*




*New York Times, March 13, 2008*

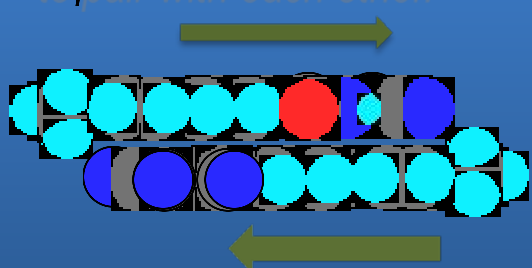
# Molecular Engineering of Nonlinear Optical Chromophores for Ultrahigh Speed Information Processing




This kind of molecules tend to have large dipoles

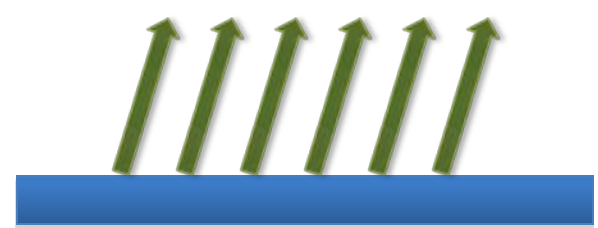
Electron Donor — $\pi$-Conjugated Bridge — Electron Acceptor

*Just like stacking magnet pellets: The dipole of chromophores tend to pair with each other.*



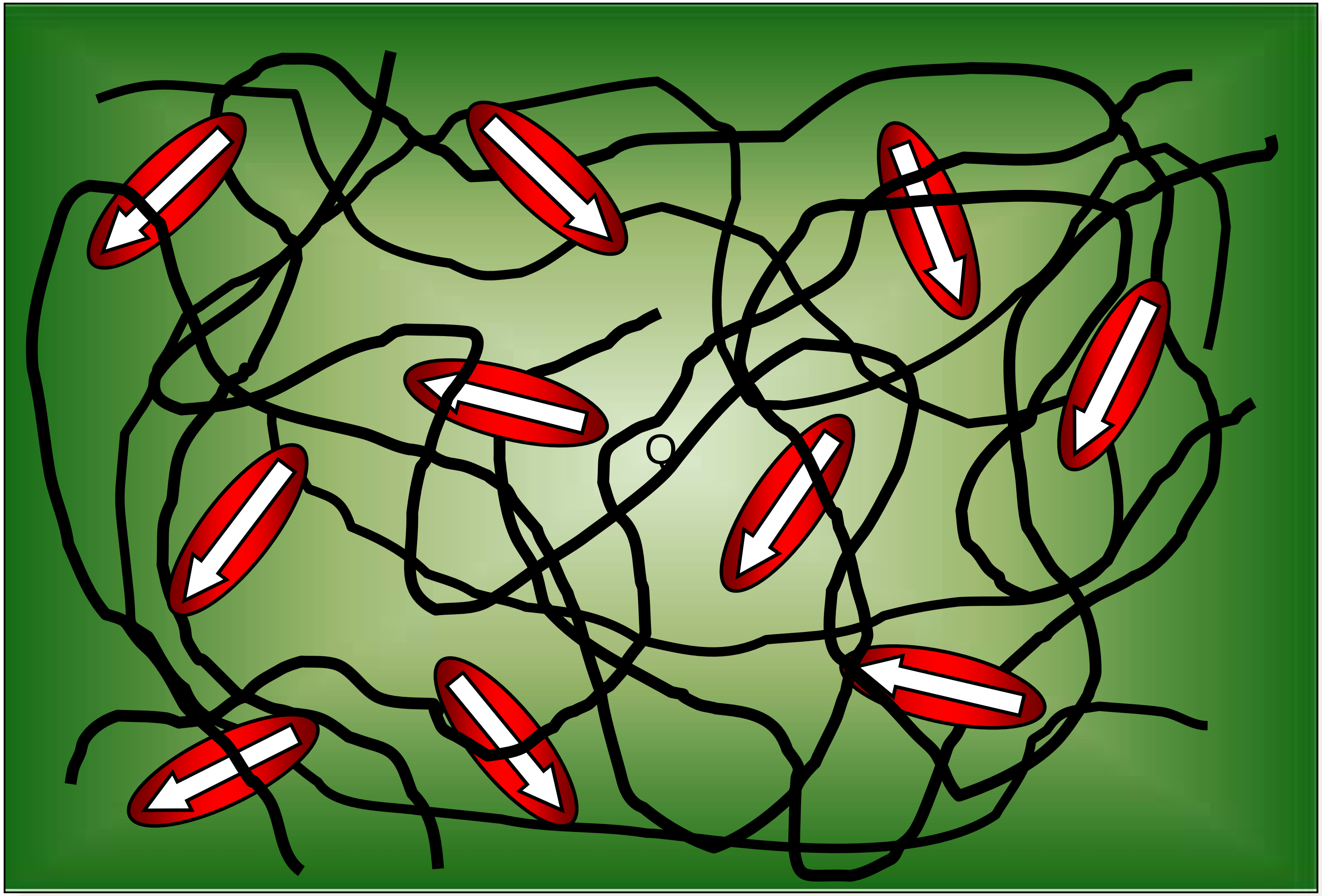
*But*

*We prefer them to be oriented in this manner:*



# Need to Align Dipolar Chromophores in Polymers

*(The criterion for showing EO activity for signal modulation)*



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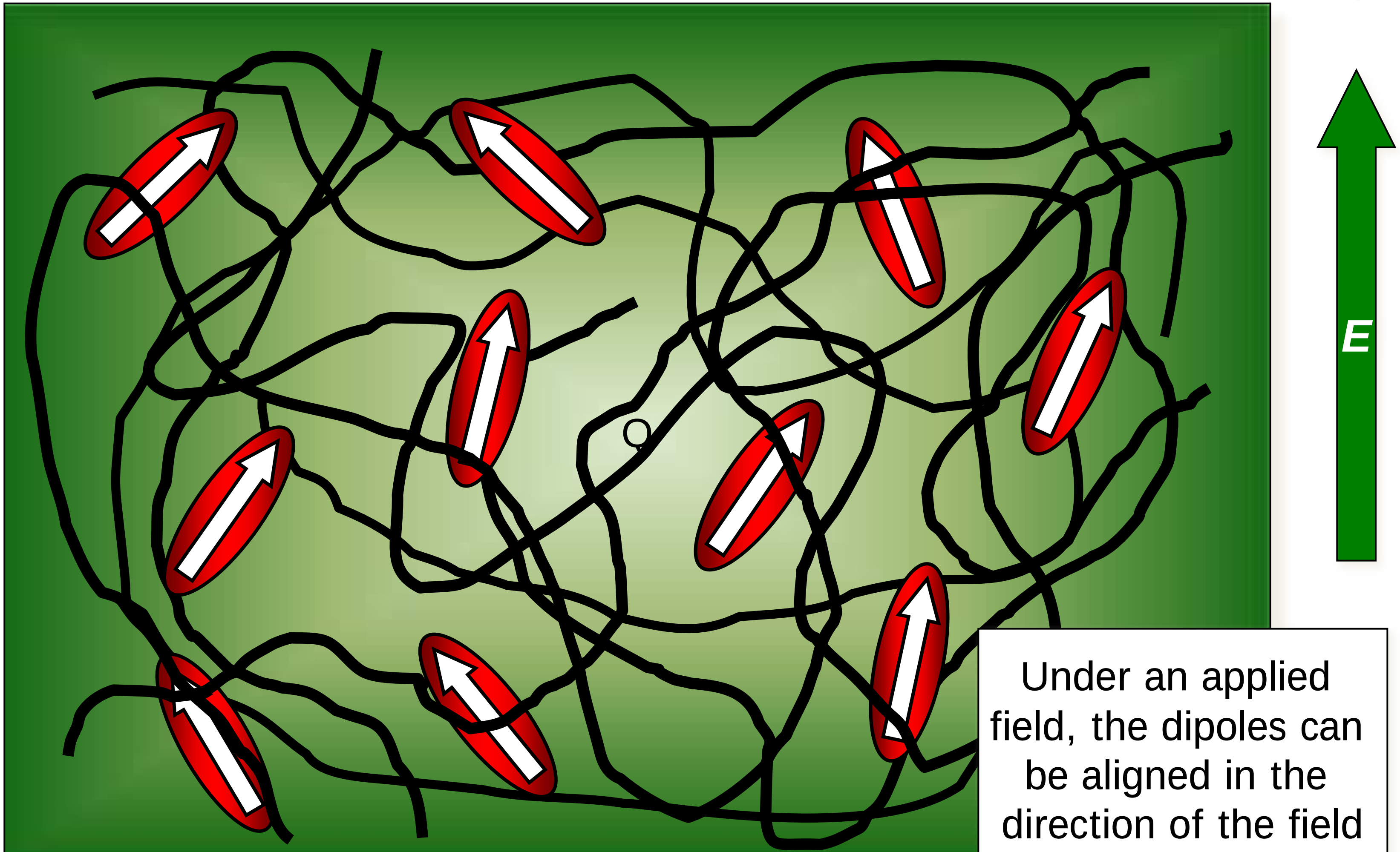
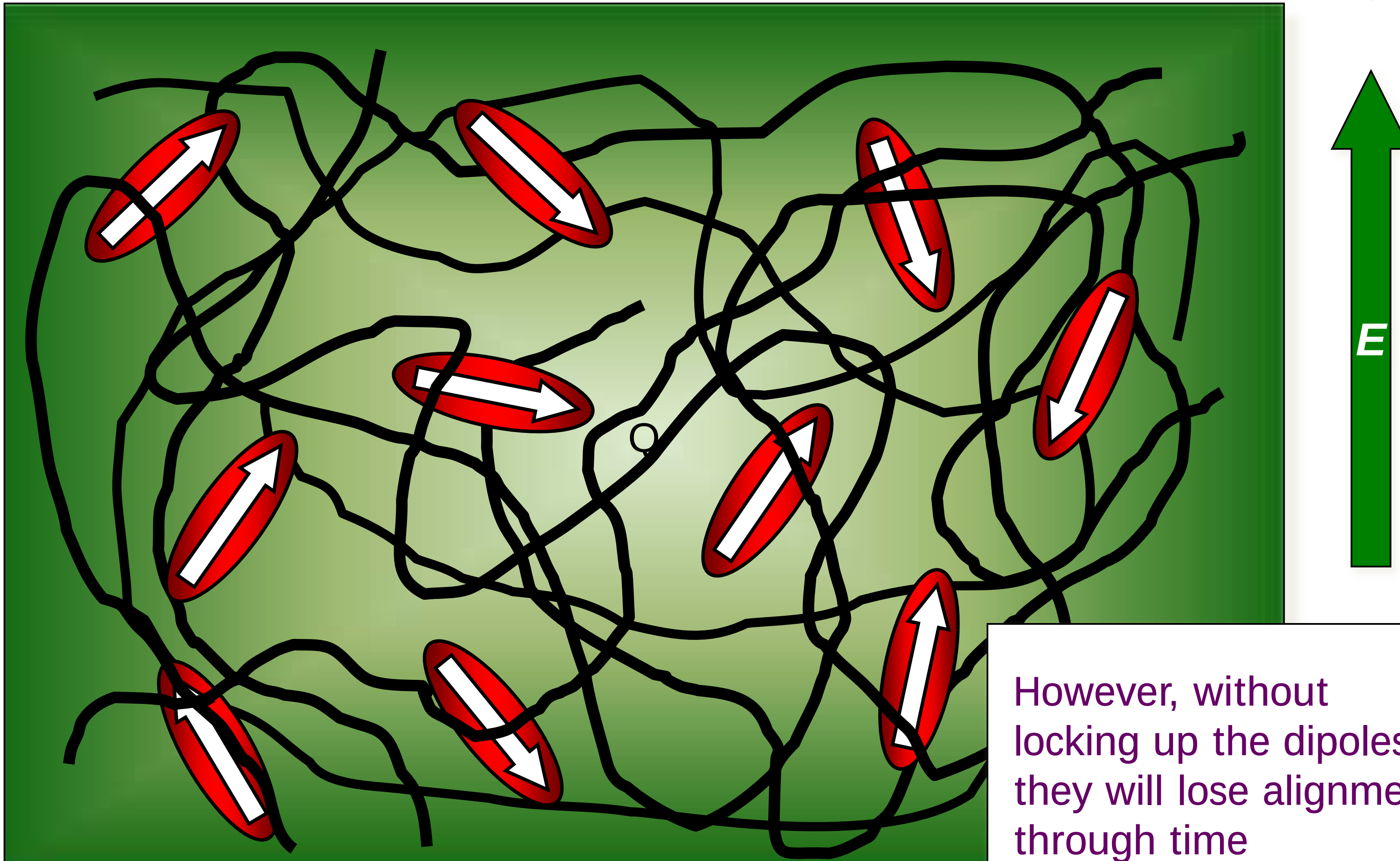



Under an applied field, the dipoles can be aligned in the direction of the field

# Need to Align Dipolar Chromophores in Polymers

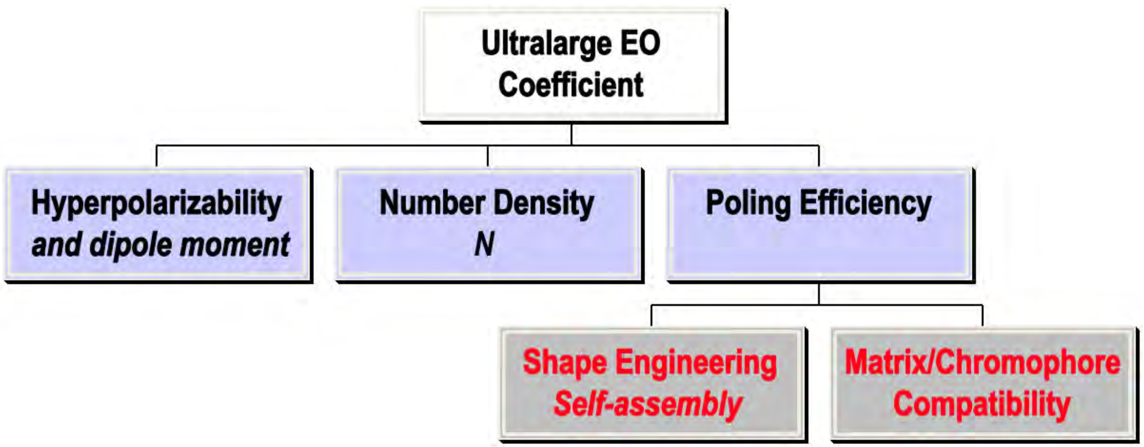
*(The criterion for showing EO activity for signal modulation)*

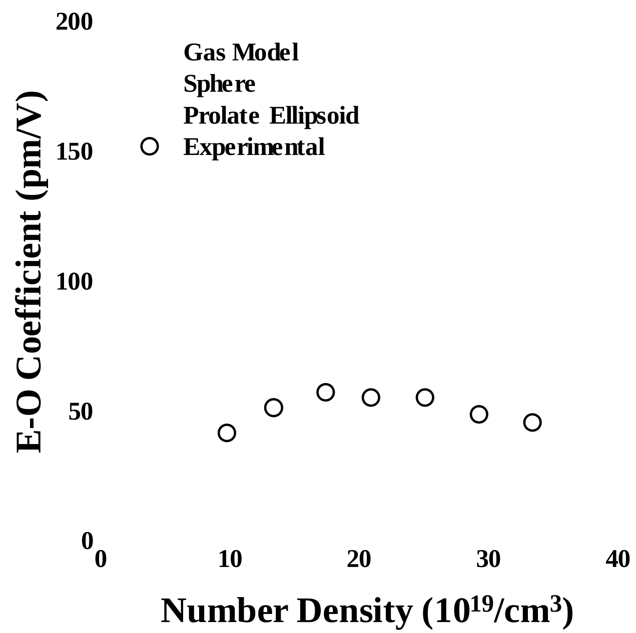



However, without locking up the dipoles they will lose alignment through time

# Translating Molecular Optical Nonlinearity into Macroscopic Electro-optic Activity

$$r_{33}(-\omega, \omega, 0) = 2N\beta f(\omega)f(\omega)f(0)\langle\cos^3\theta\rangle/n^4$$





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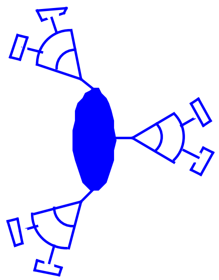
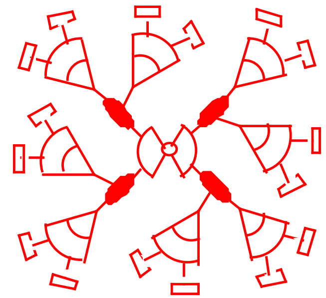
# Nanoscale Tailoring of NLO Dendrimers and Polymers for Electro-Optics

**Dendron-modified NLO chromophore for high $T_g$ polymer matrix:**



Chem. Commun., 2002, 888.

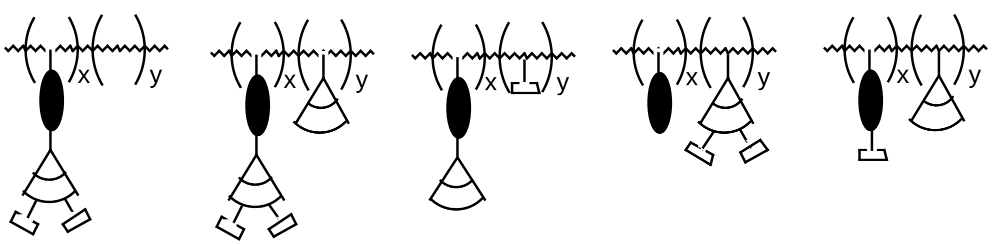
**Crosslinkable multi-chromophore containing NLO dendrimer:**



JACS 2001, *123*, 986.
Adv. Mater., 2001, *13*, 1201.

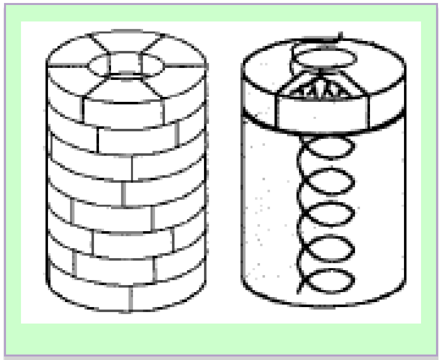
**Crosslinkable Dendronized NLO polymer:**

1) Introduce dendritic silte-isolation effect
2) Maintain the processability of linear polymer



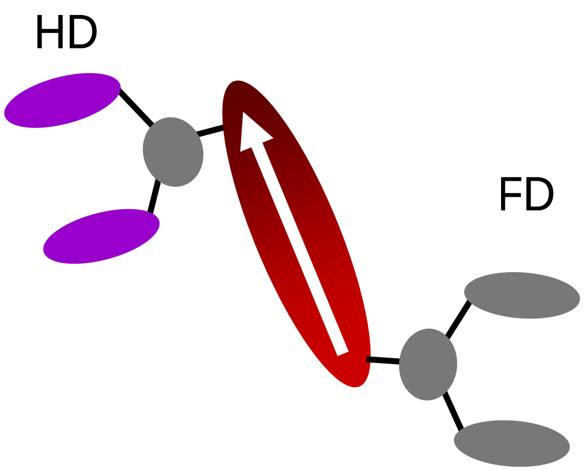

Adv. Mater., 2002, *14(23)*, 1763.

J. Phys. Chem. B, 2004, *108*, 8523.



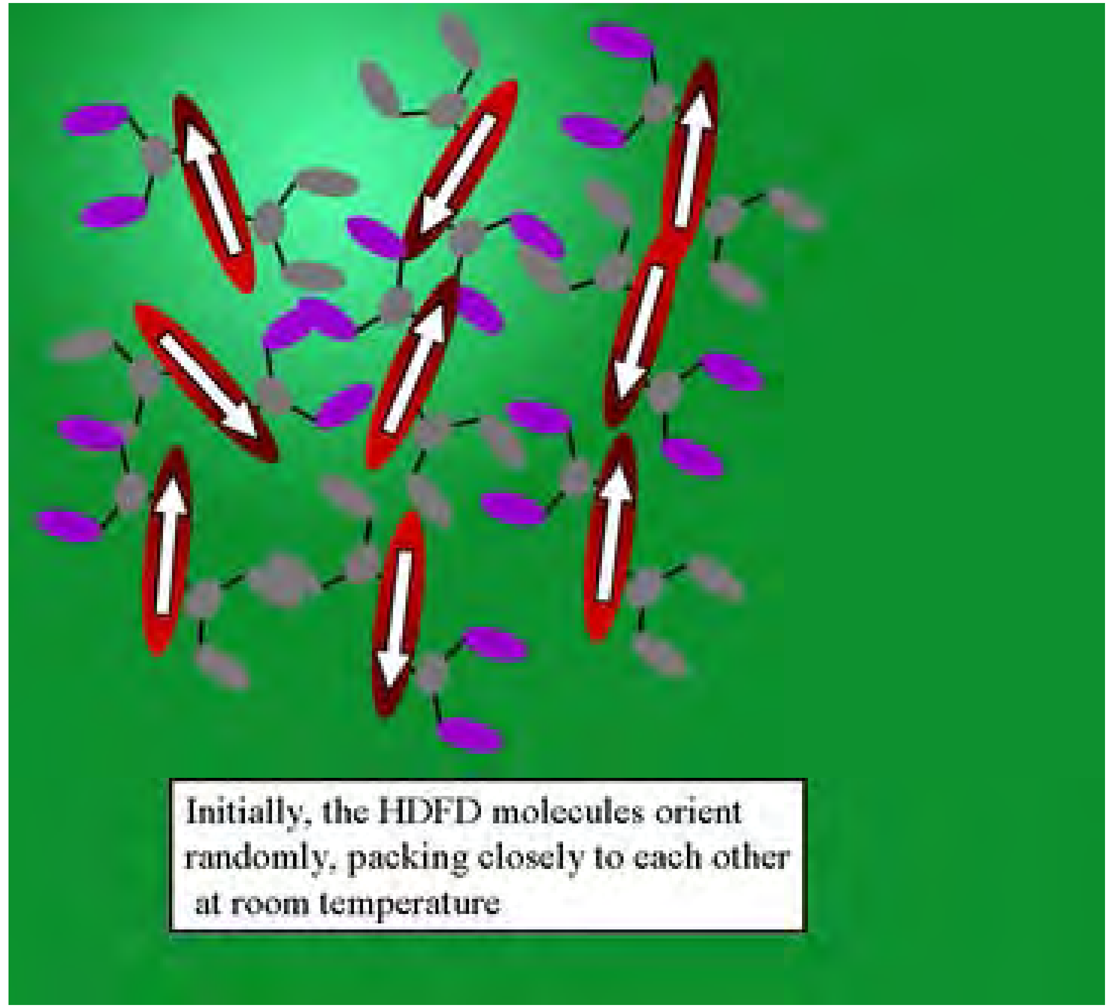
Nano Lett., *2008, 8(2), 754.*

# Enhanced Alignment Efficiency and Stability by Exploring Supramolecular Interactive Forces

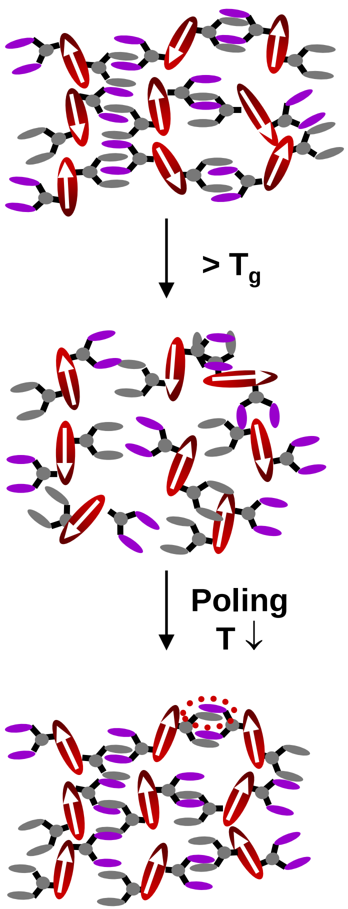


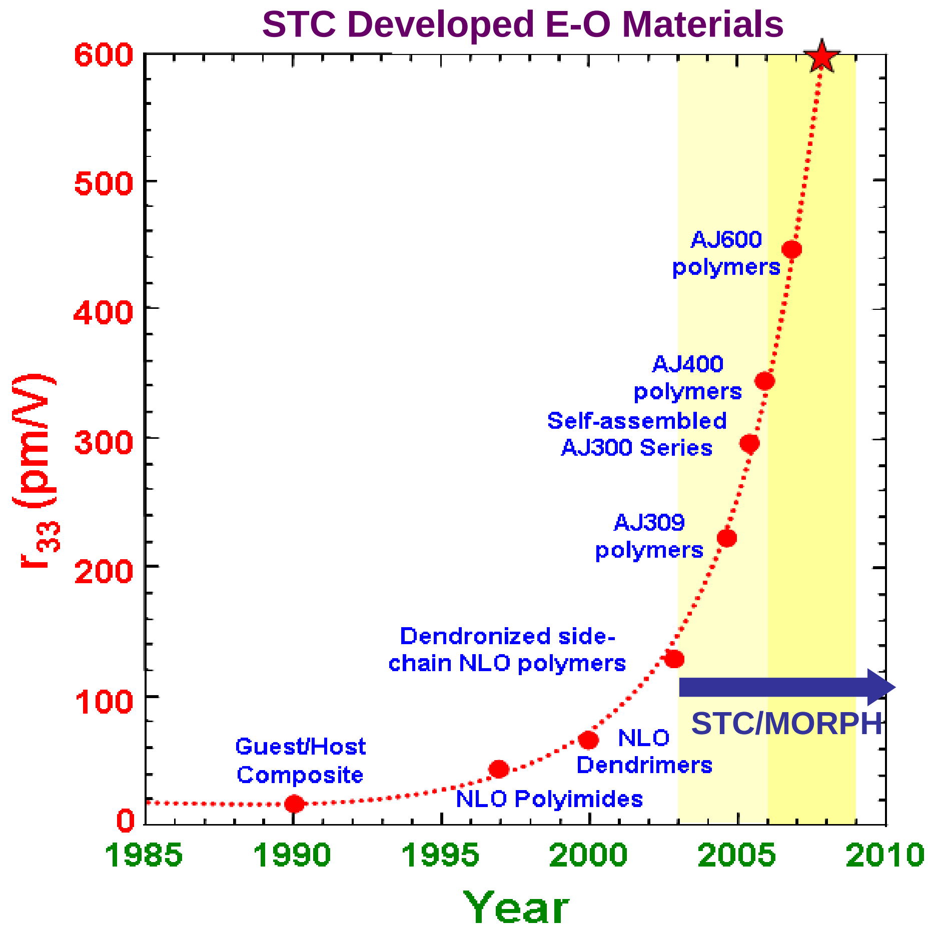

*HD & FD act not only as steric bumpers to separate dipoles but also possess self-recognition capability to assemble themselves*

*<u>J. Am. Chem. Soc,</u> 2007,* 129, *488.*



# Supramolecular Electro-Optic Dendrimers Exhibiting Ultralarge E-O Activity



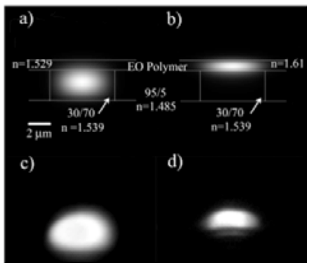




Jen & Dalton, *J. Am. Chem. Soc.* 2007, 129, 488; Jen & Overney, *Nano. Lett.* 2008, 8, 754; Jen, *Adv. Mater.* 2009, 21(19), 1976.

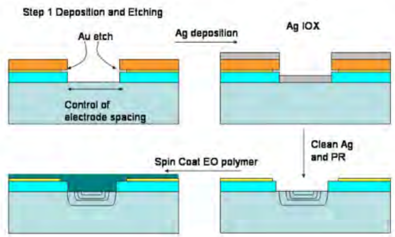
# Organic E-O Materials with Properties Tailored for Enhancing High-Speed Information Processing and National Security

Exceptional organic E-O materials (such as large $r_{33}$, cryogenic temperature operation, and excellent thermal stability) have been achieved through rational design of dipolar chromophores, supramolecular assembly of dendrimers, and click chemistry and controlled lattice-hardening of macromolecules.

## Hybrid EO polymer/IOX glass modulator fabrication



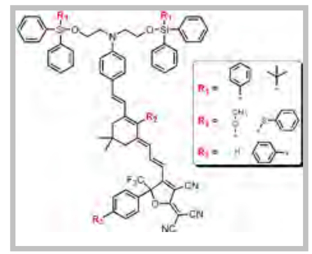

*Low-loss strip modulator design (top) and measured beam profiles*

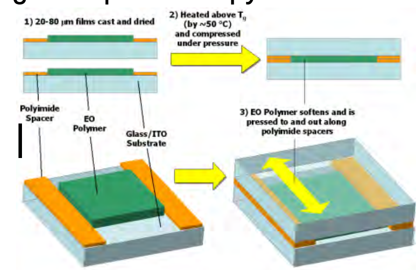



*EO polymer/IOX modulator with 4dB of insertion loss demonstrated*

Strip loaded hybrid modulator 2.8V, 5.7dB IL, *Optics Express* 17, 3317.

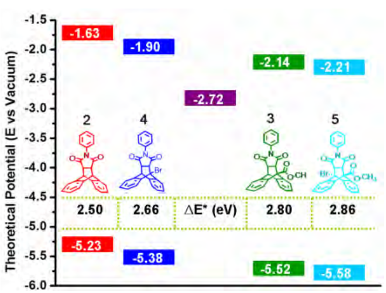
## Materials engineering of E-O polymers enable thick-film processing for THz sensing and spectroscopy

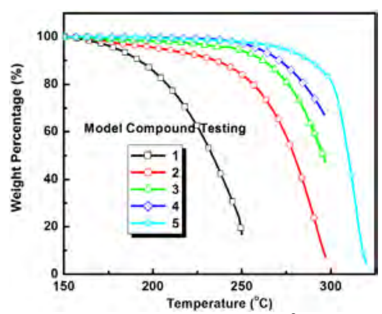





Hot embossing using highly efficient and thermally stable chromophores has enabled the fabrication of thick, smooth, and defect-free films of EO polymers.

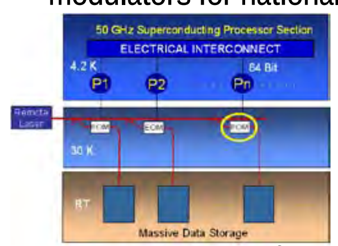
## Highly Stable E-O polymers allow Intel to fabricate CMOS photonic devices for high-speed chip scale interconnect

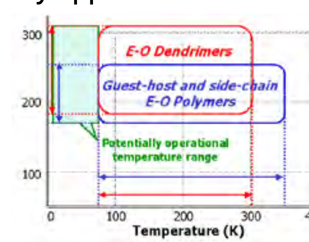



Crosslinked EO polymers showed isothermal stability ≥ 250° C.

## E-O materials enable the fabrication of low $V_\pi$ cryogenic modulators for national security applications




Reduced power requirements for petaflop supercomputing enabled by high speed, low temperature, EO modulators with very low drive voltage, which can be achieved by a new series of organic EO materials exhibiting large $r_{33}$ values and operational stability from ambient temperature to cryogenic temperatures (40 K).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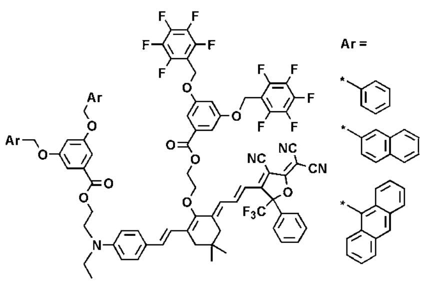
## Supramolecular assembly of dendrimers exhibiting ultralarge E-O activity and enhanced thermal stability



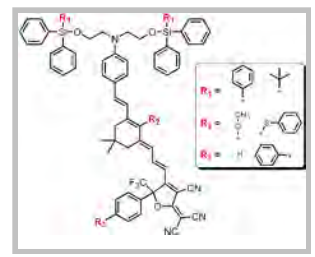

Enhanced cohesive energy of heterodimers and structural rigidity

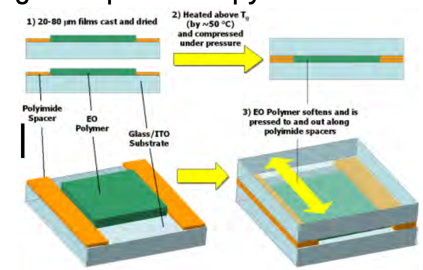
$r_{33}$ values: 270-318 pm/V @ 1310 nm;

Temporal stability: 90% @ 85 °C for 300 hrs.

Jen et al, *Adv. Mater.* 2009, 1976.

## Materials engineering of E-O polymers enable thick-film processing for THz sensing and spectroscopy



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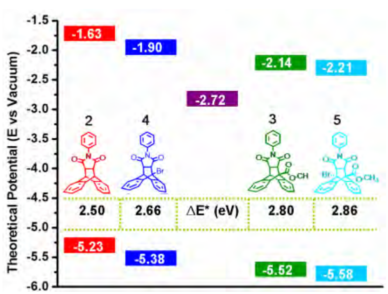


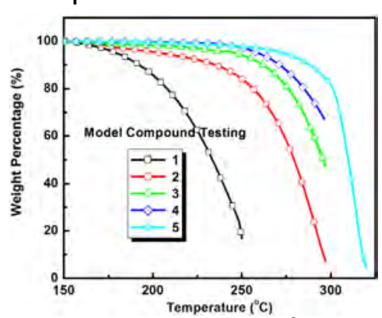


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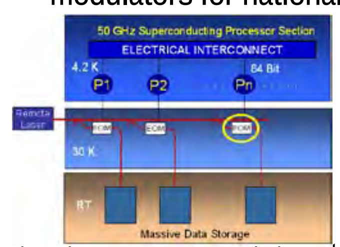


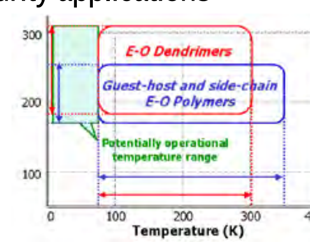


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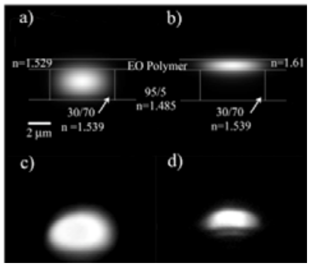
# E-O Polymer Enabled Low Drive Voltage, Low Loss Hybrid Polymer / Sol-Gel Modulators

ACHIEVEMENTS: The primary achievement has been the reduction of device loss ( < 4dB) through the development of hybrid EO polymer/ion exchange glass modulators (1.5cm long). The high speed performance of our sol-gels has been confirmed by high frequency dielectric loss measurements on coplanar structures, while high speed packaging has been enabled by the development of wirebonding. A new Mach-Zehnder EO polymer characterization system has been developed and provides direct measurement of electro-optic and piezo tensor coefficients.

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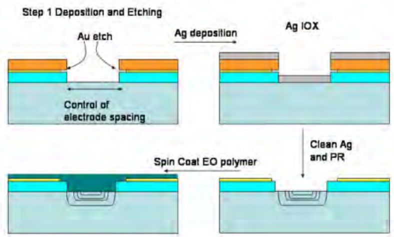



*EO polymer/IOX modulator with 4dB of insertion loss demonstrated*

Strip loaded hybrid modulator 2.8V, 5.7dB IL, *Optics Express* 17, 3317.

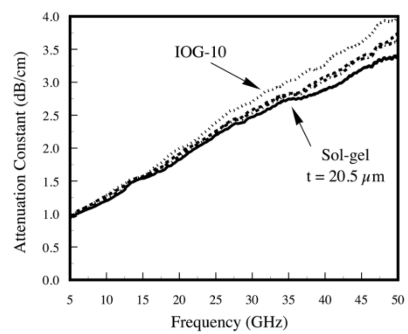
IMPACT: We have continued the drive towards low insertion loss, low-voltage modulator. A hybrid approach has been developed that combines low-loss (0.1 dB/cm) ion exchange waveguides, grey scale masking and versatile EO polymers such as AJL50. Results demonstrate passive waveguide losses < 4dB, unprecedented for EO polymers. A wavelength/frequency agile MZ EO polymer characterization system enables direct measurement of properties crucial for coplanar waveguide devices and spatial light modulators. Excellent microwave performance has been confirmed for our sol-gels (@40GHZ) and we have demonstrated wirebonding for reliable, microwave contact.

## Mach-Zehnder EO characterization system

MZ EO polymer measurement system provides measurement of $r_{33}$, $r_{13}$, their ratio and piezoelectric coeffcient

- Measurements on UW "blind" samples in excellent agreement with Teng-Man measurements
- Criitical information obtained needed for IOX coplanar electrode modulator design and optimization of SLM and modulator devices

## High-speed device development




High frequency dielectric loss of sol-gel is as low as glass

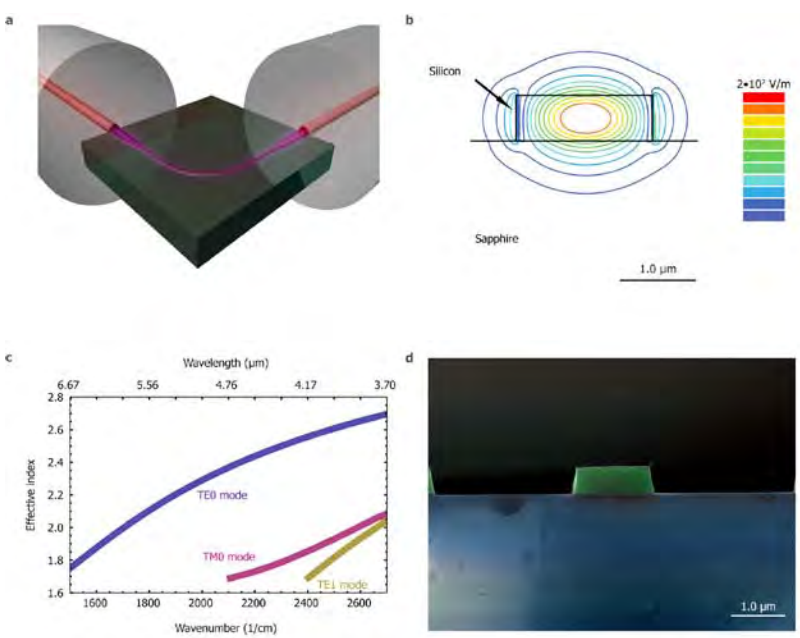
Wirebonding hybrid modulator

# Silicon Waveguides for the Mid-Infrared

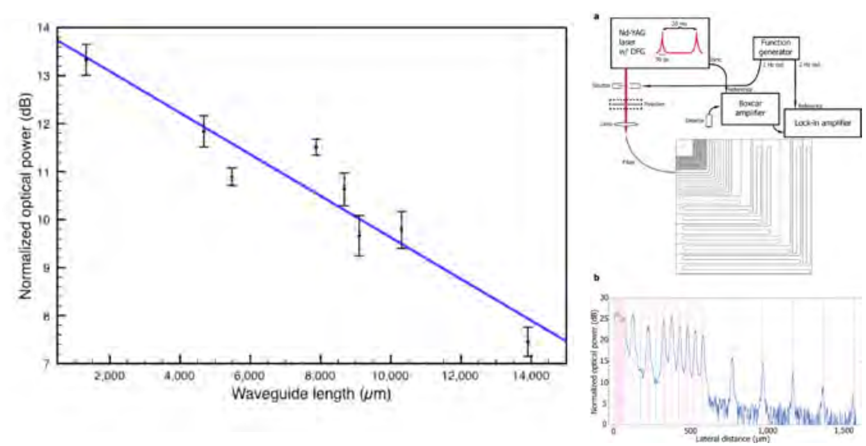
ACHIEVEMENTS: Silicon-on-Sapphire allows wave guiding in high-confinement silicon guides well into the mid-infrared, and we have demonstrated low-loss guides in the mid-IR for the first time.

IMPACT: We have developed the world's first integrated waveguides for the mid-infrared. This region is critically important for spectroscopy, infrared imaging, remote sensing, and military applications in areas such as infrared countermeasures. In addition, one of the most prominent applications for nonlinear polymers developed at the STC MDITR Center is in ultrafast nonlinear photonic: By creating waveguides in silicon that can guide across very wide spectral regions, we open the possibility of new mid-infrared sources based on chip-scale nonlinear processes in waveguides. Losses as low as ~5 db/cm have recently been demonstrated.

**Silicon-on-Sapphire Waveguide Designs and Cross-Sections**




**Optical Testing System and Waveguide Loss Results**



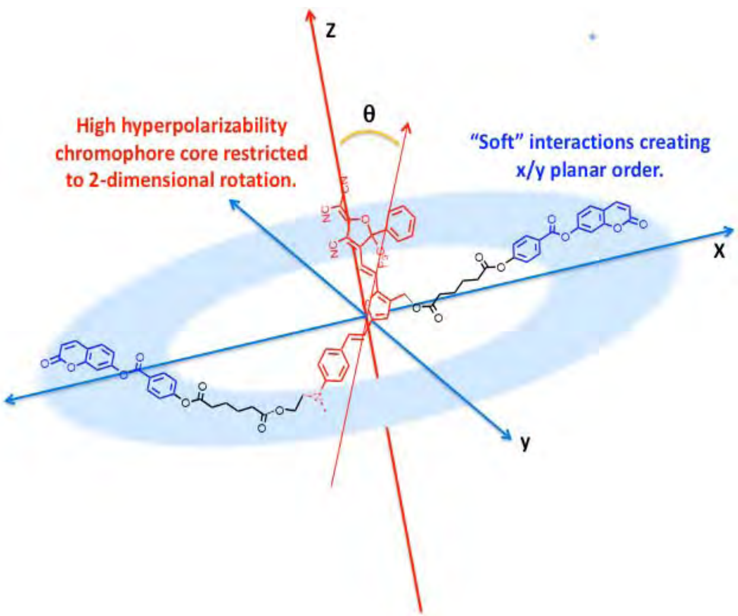


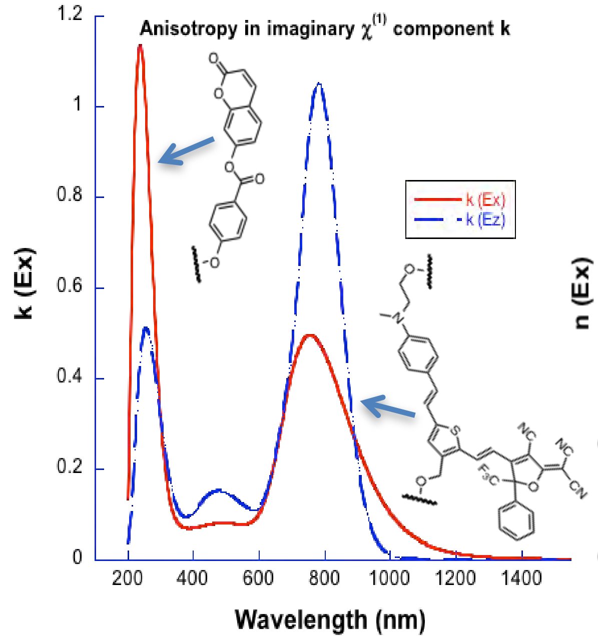
UNIVERSITY of WASHINGTON

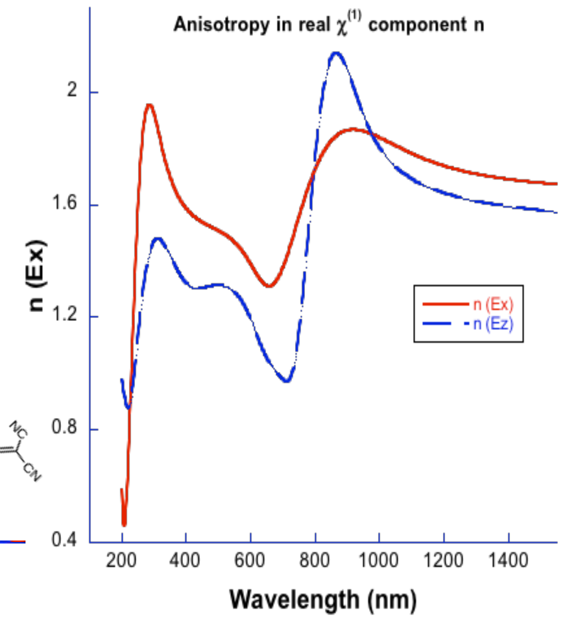
Hochberg

# Spectroscopic Measurements of Poling-induced Polar Order

ACHIEVEMENT: Variable Angle Spectroscopic Ellipsometry ( VASE) and Variable Angle Polarized Referenced Absorption Spectroscopy (VAPRAS) have been utilized to measure the poling-induced order of chromophoric components in multi-component electro-optic materials.



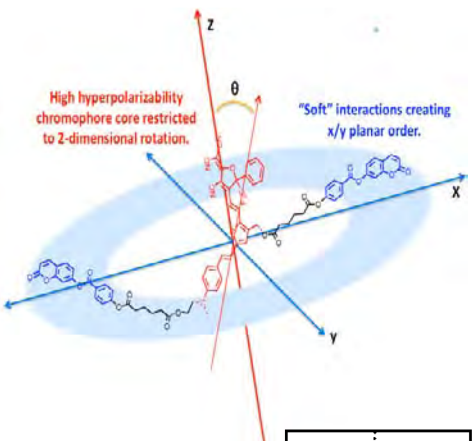



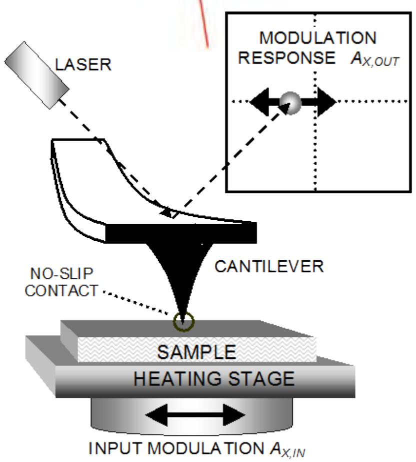



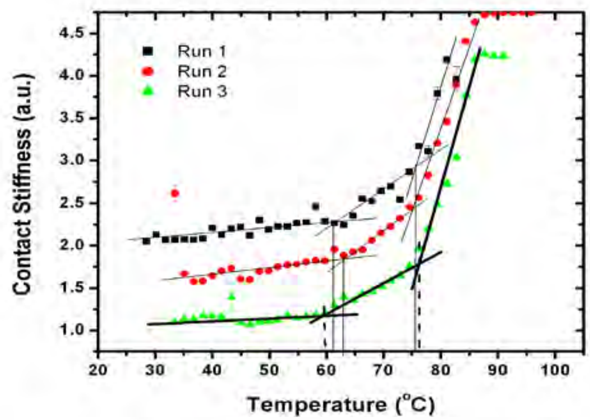

VASE results (shown above) permits determination of the relative orientation of the electro-optic chromophore and the LC mesogen and the poling-induced order of these moieties in the electro-optic material shown at the left. These results can be compared with theoretical simulation results.

# Spectroscopic Measurements of Poling-induced Polar Order

**ACHIEVEMENT: Force Modulation Scanning Probe (FM-SP) and Intrinsic Friction Analysis (IFA) have been used to define intermolecular electrostatic interactions important in defining poling induced order.**




FM-SP and IFA, together with Dielectric Relaxation Spectroscopy (DRS), permit definition of the activation entropy and relaxation length scale associated with the intermolecular cooperativity induced by specific spatially-anisotropic