APPLIED RESEARCH & PHOTONICS INC

nanoPhotonic Integrated Circuit (nPIC)

Electro-optic Dendrimer based Terahertz Waveguide

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Plan

- Introduction/Company
- Dendrimer
- Terahertz generation/Electro-optic Route
- Modeling, Simulation, Data
- Other photonic components
- Concluding Remarks

NanoPhotonics

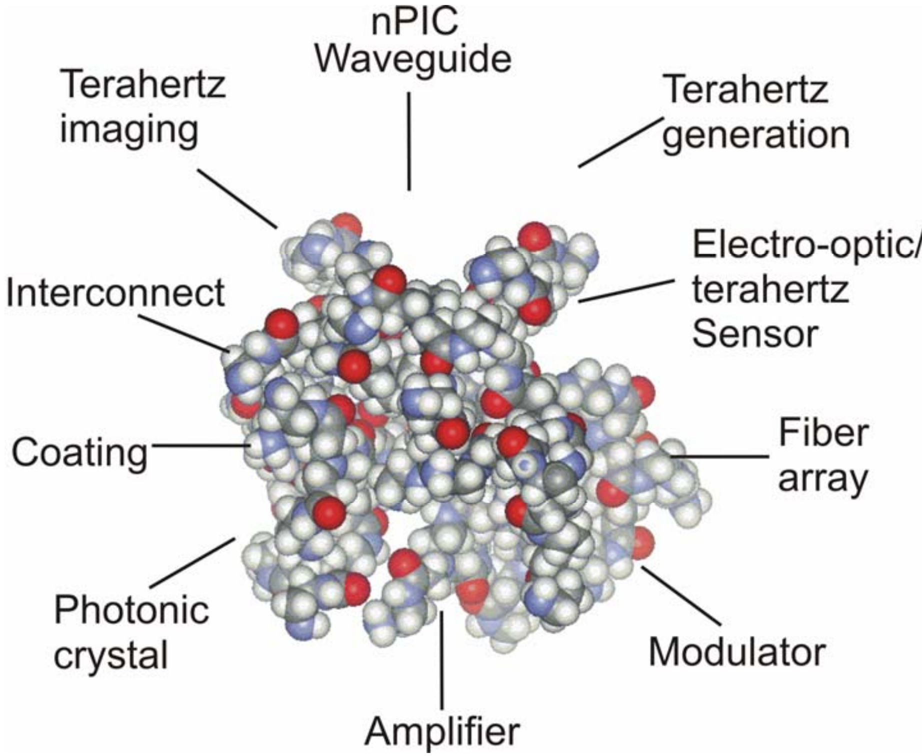
- **An opportunity to create smart devices by combining <u>nanotechnology</u> and <u>photonics</u>**
- **1880 Bell: *Photophonic transmitter***

- **1905 Einstein: *measured sugar molecule size ~ 1 nm***
- **1985 Tomalia: Dendrimer**
  - **a polymeric nanomaterial**
  - **allows to combine the power of nanotechnology and photonics**
  - **can result in a number of important applications**

Dendrimer

A polymeric nanomaterial

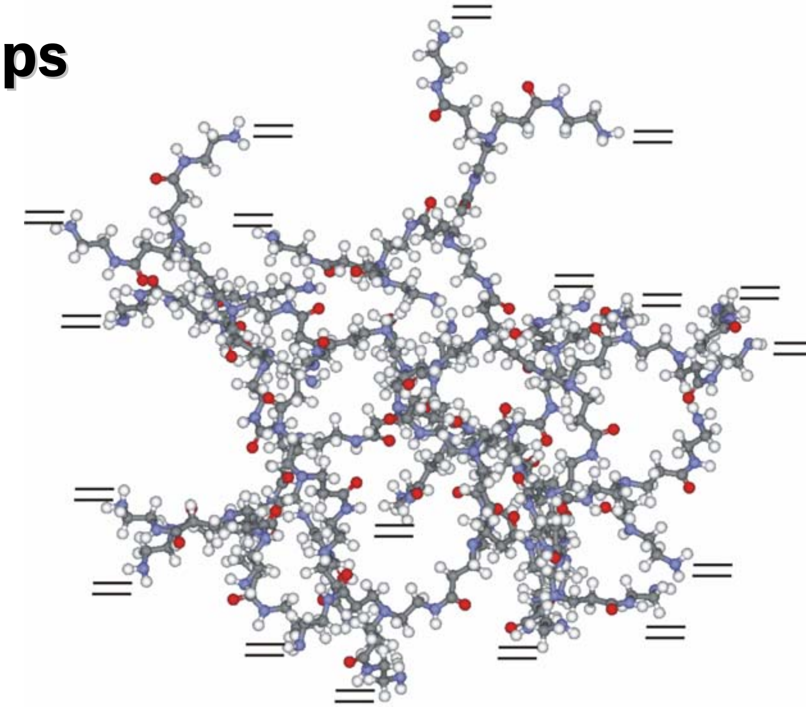
- 3-D, core-shell molecule
  Generation: G0-G11
  Size: 4-12nm
- Multiple functionality: terahertz waveguide, modulator, amplifier, and band gap
- Established route for transition to production
- Cost-effective



Multifunctional dendrimer molecule

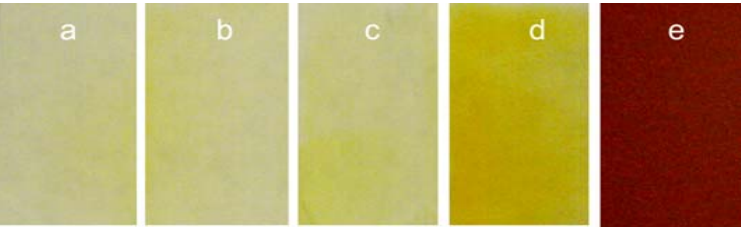
Multivalent dendrimer

- No. of end groups: $2^{(G+2)}$, G = 0 to 11
- *G*3 PAMAM dendrimer: 2^5 = 32 groups
- each molecule can accept up to 64 dopant molecules
- Potentially 64 fold increase of $\chi^{(2)}$ for *G*3
- Higher for higher generation
- High field poling required
- There are many chromophore to choose from

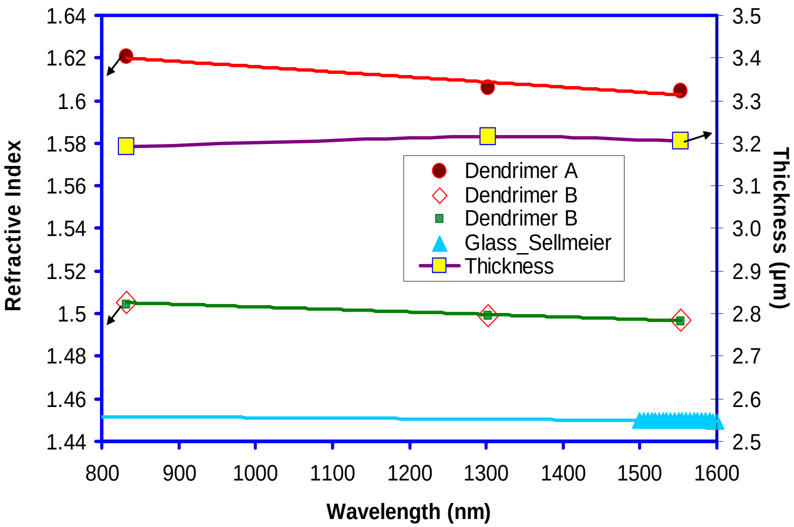


$$\chi^{(2)} = n F \beta \langle \cos^3\theta \rangle$$

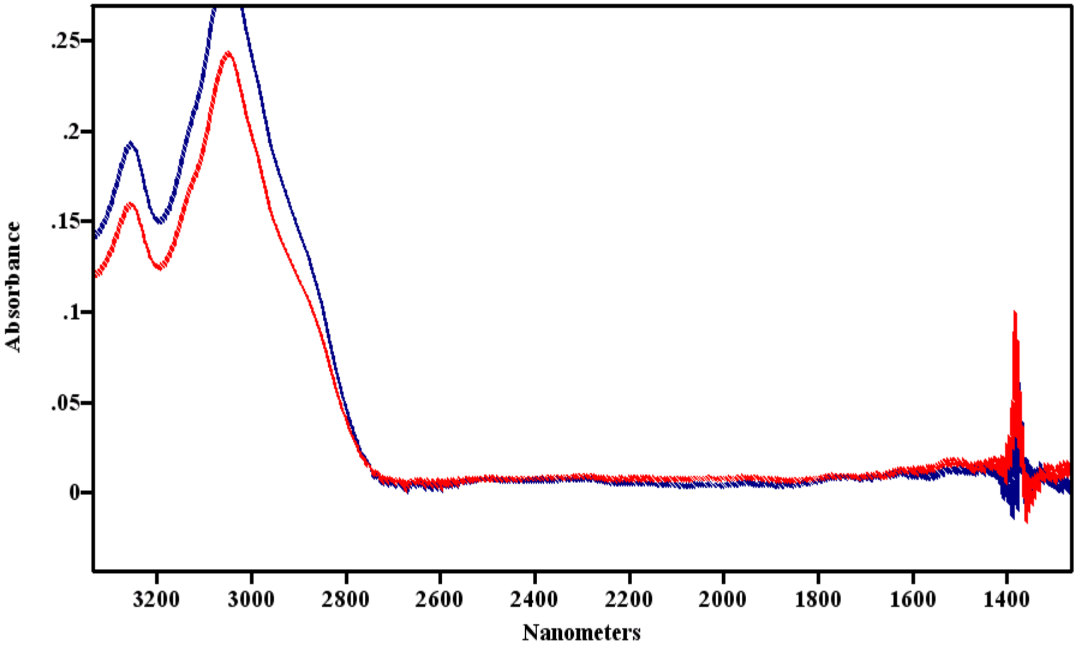
Optical properties



Variation of refractive index of cured dendrimer film compositions by natural index contrast (NIC) method



Dendrimer film's RI can be controlled by its generation, doping, and process parameters



FTIR spectra of dendrimer film exhibits high transmission over the NIR region.

Terahertz waveguide

- EO rectification
- waveguide
- Photoconductor
- Reactor/Accelerator

Principle of THz generation in a waveguide

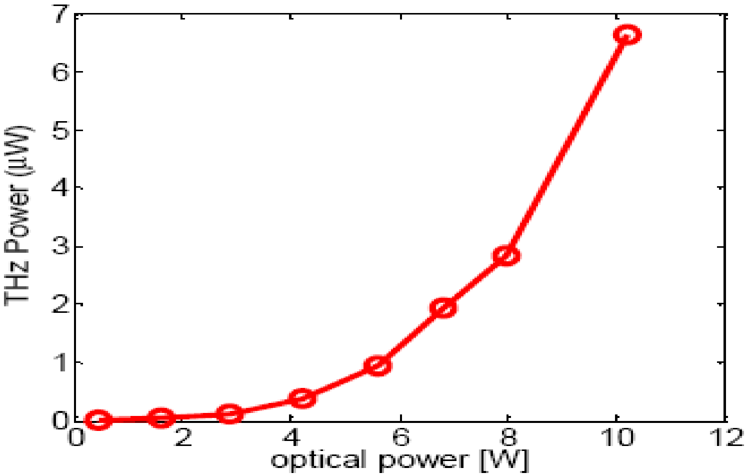
$$E_{THz,\max} \propto \chi^{(2)} E_{pump}^{2}$$

- Terahertz power is proportional to the electro-optic coefficient and to the square of input pump power.

- EO rectification in waveguide is scalable, not limited by heat dissipation or emission saturation:

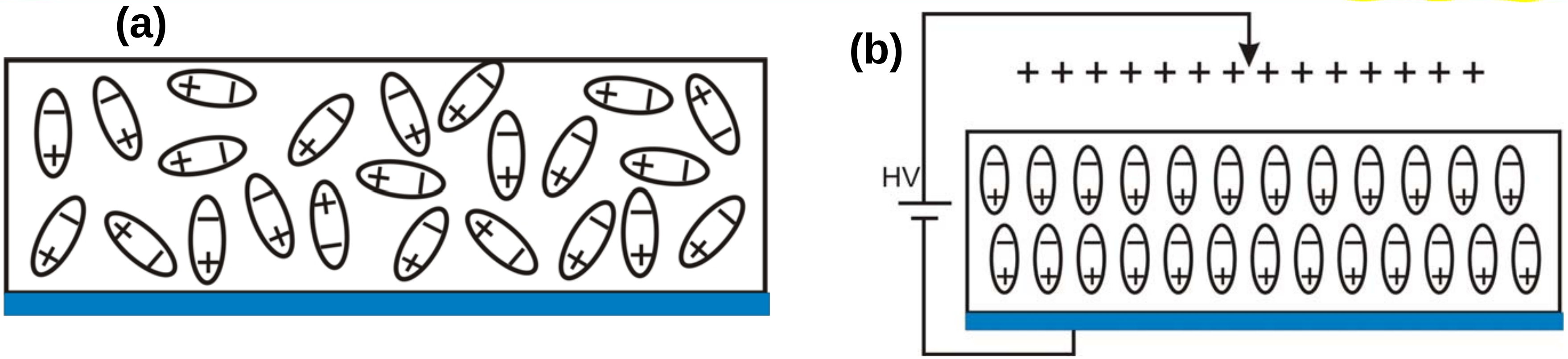
$$w_{THz} = f(w_{\mathrm{p}}, r_{33}, I_{eff}, A)$$

w_p: pump power, r_{33}: EO coefficient
I_{eff}: effective intensity, A: # of waveguide in array

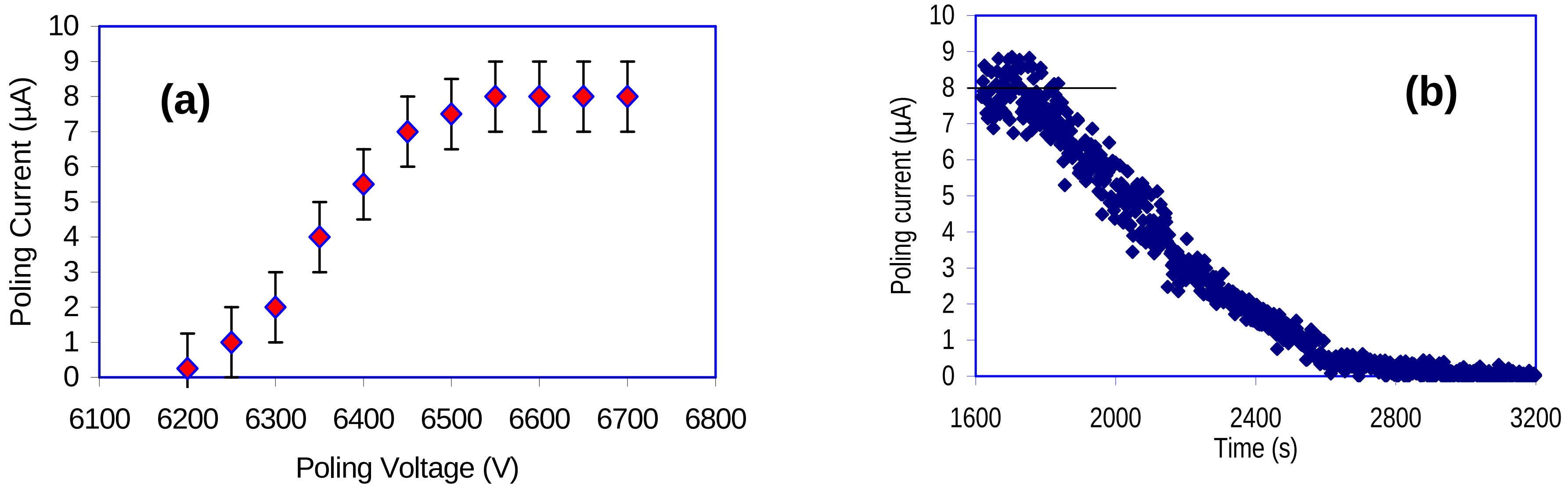


THz power scaling as a function of pump power in GaP: approx. quadratic. Ref. Chang, et al., *OP. EX.*, **14**, 7909, (2006)

EO Properties: poling

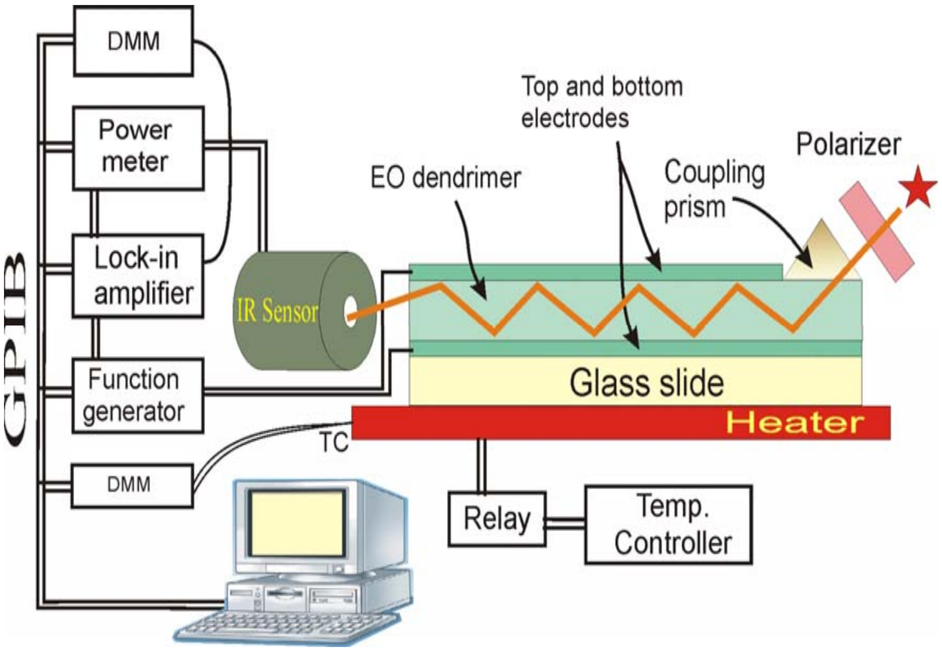


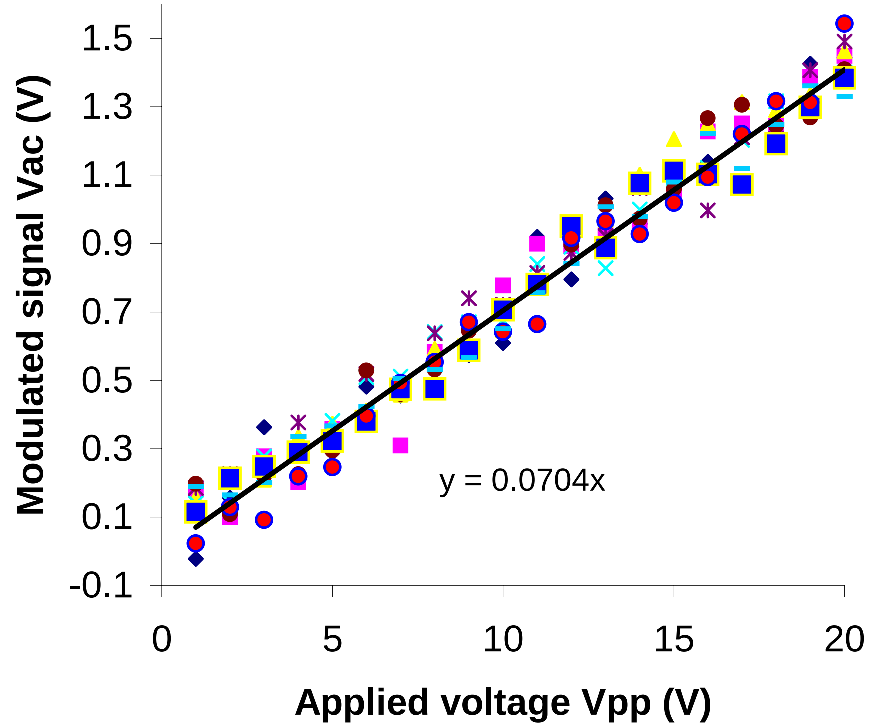
Sketch of dipole orientation in (a) unpoled and (b) corona poled dendrimer film.



(a) Poling I-V, and (b) decay of poling current in dendrimer film.

EO measurements

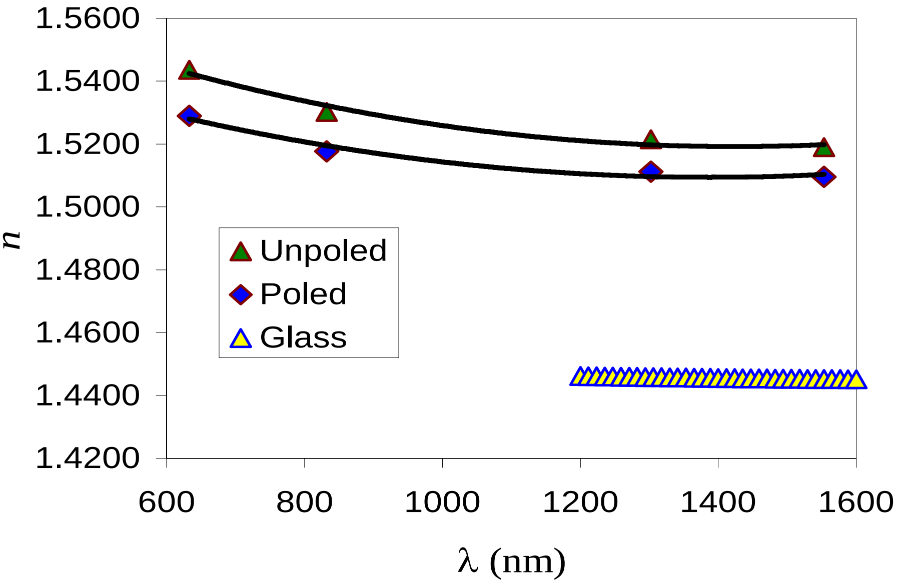


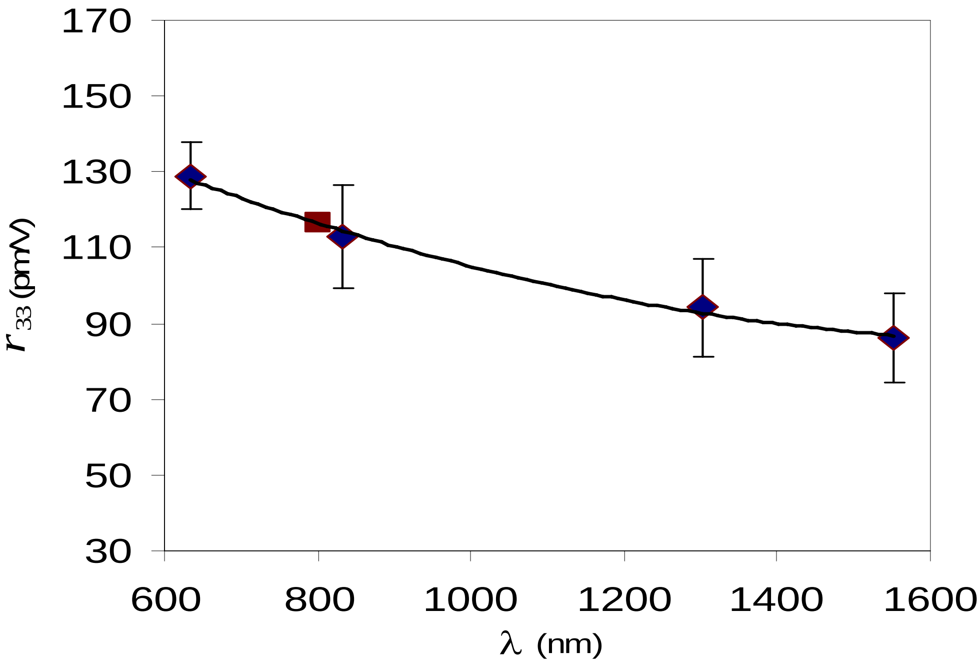


Poled dendrimer film exhibit excellent linear relationship between modulated-beam signal, Vac and applied voltage Vpp

Refractive Index & EOC

Pockels effect



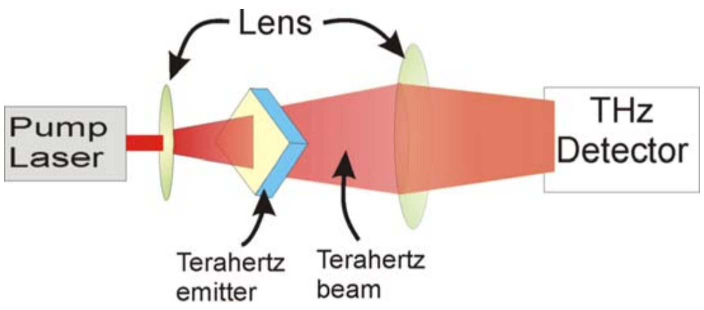


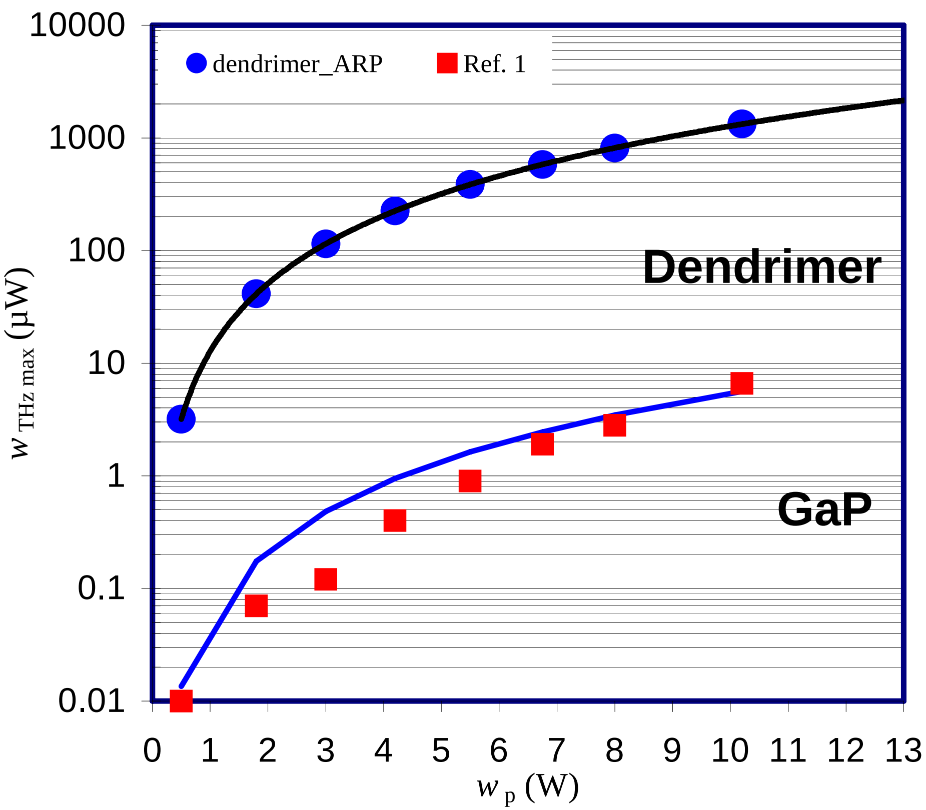
- **Refractive index difference between poled and unpoled dendrimer (Metricon 2010).**
- **→Dendrimer is suitable for terahertz generation**

$$|\Delta n| = \frac{n^3}{2} r_{33} E$$

***r_{33}* ~130 pm/V @ 633nm**

High power terahertz generation

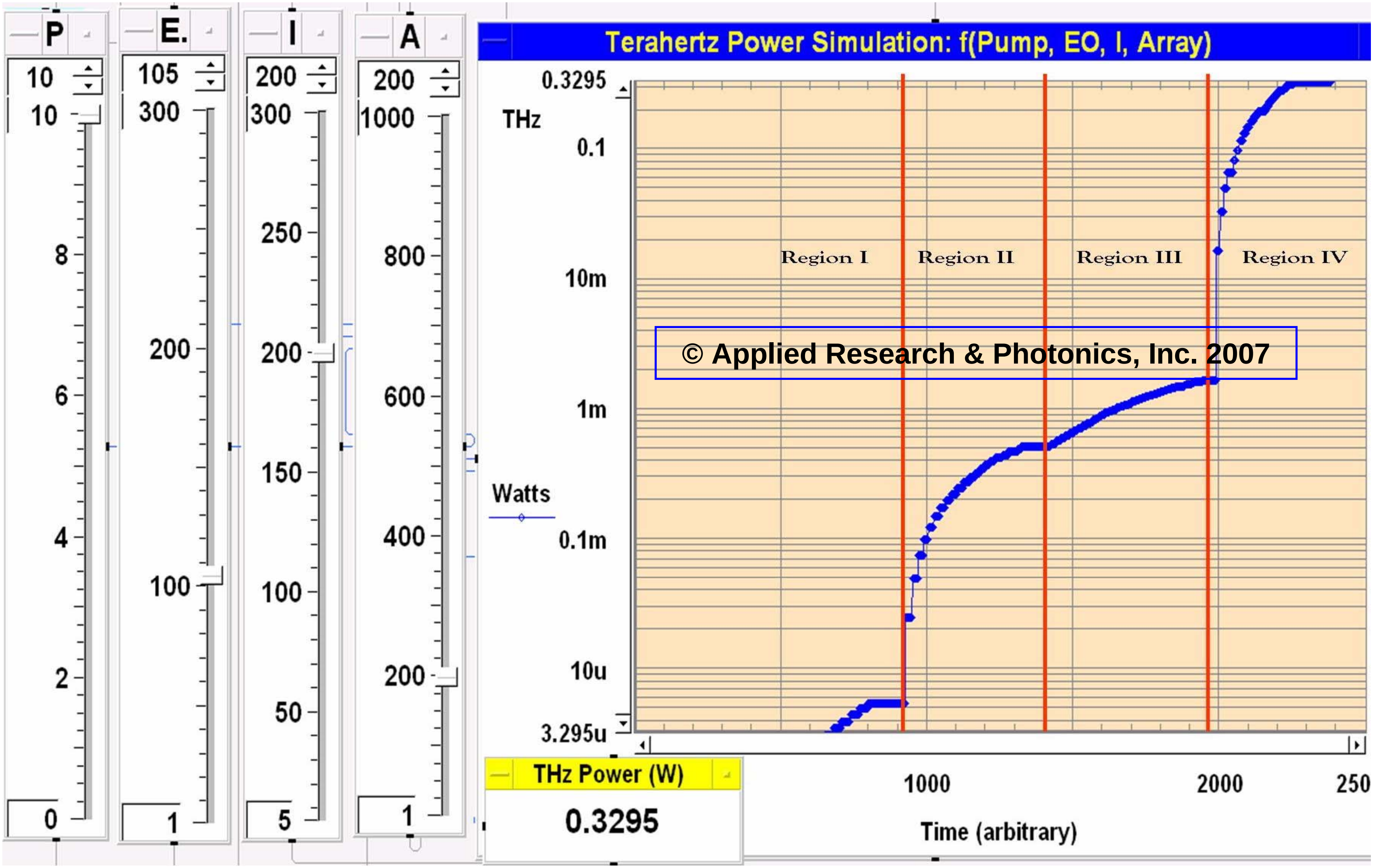




Simulation →

Red circles: data from Chang, et al., *OPTICS EXPRESS*, 14, 7909, (2006)
Yellow circles: Dendrimer: ~100 times higher power

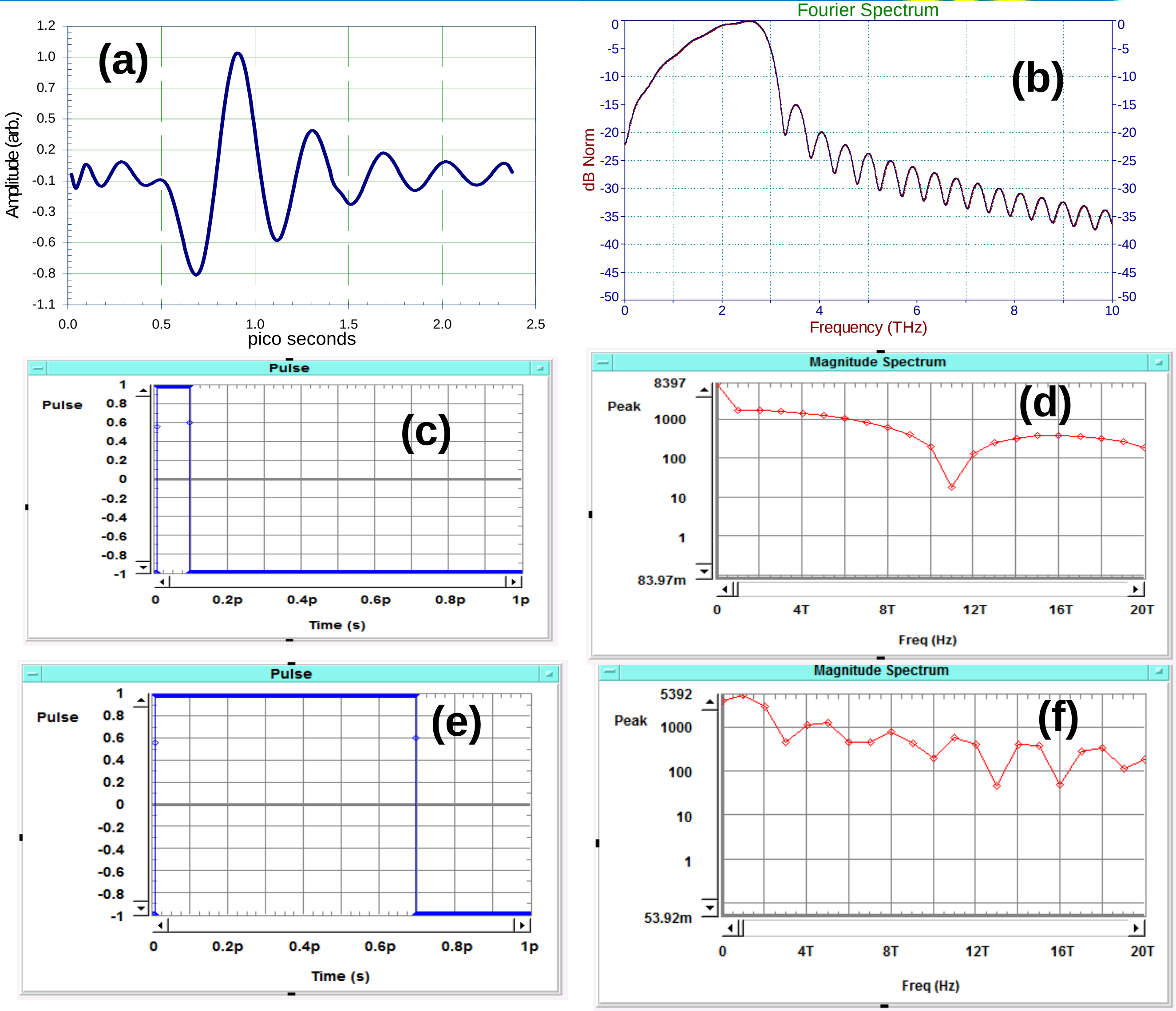
Simulation of terahertz power from dendrimer waveguide array



Terahertz Spectrum Simulation

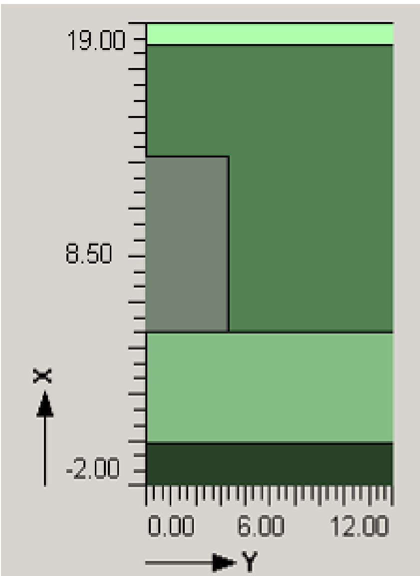
Typical terahertz pulse and spectrum (simulation):

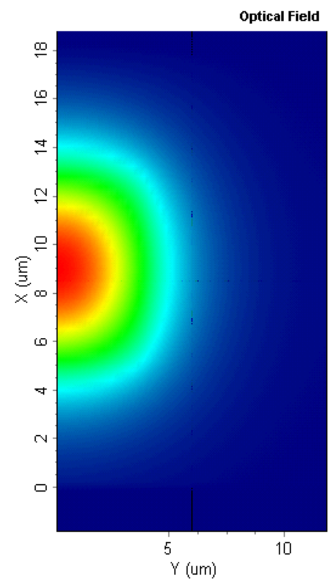
(a) A typical terahertz pulse, (b) normalized terahertz spectrum of the pulse shown in (a).
(c) and (e): pulses with width 100 fs and 690 fs, respect., at 80 MHz.
(d) and (f): terahertz spectra for (c) & (e).

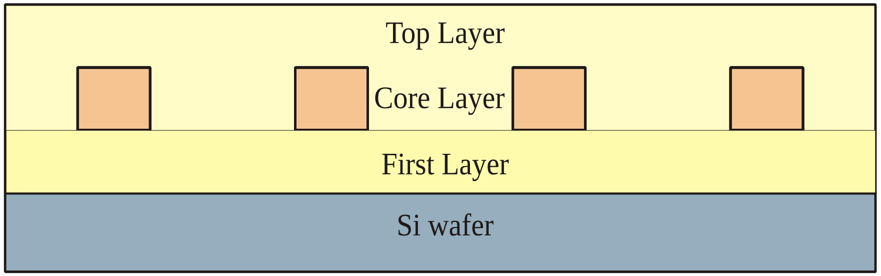


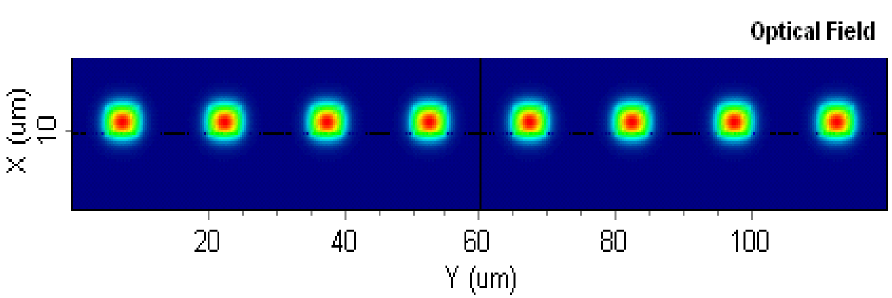
Design & Simulation

Waveguide: Core Technology







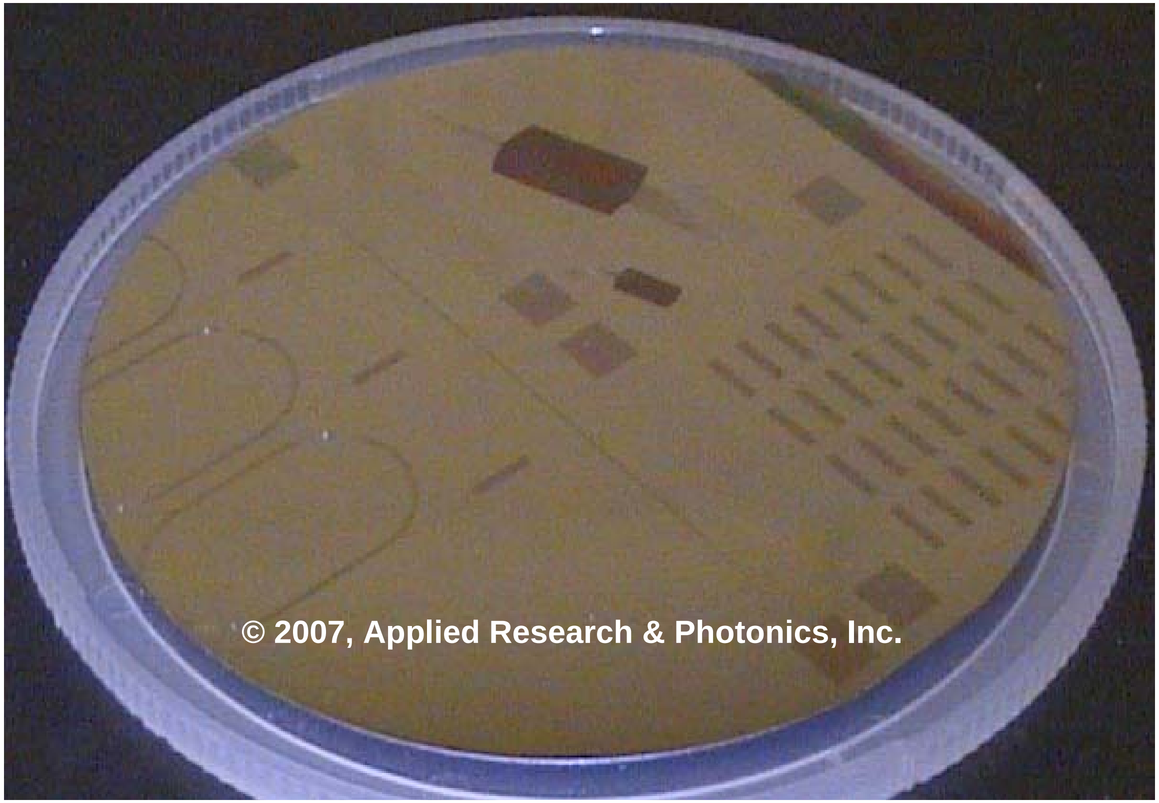


Dendrimer based waveguide design and simulation.

From left: half-core, field intensity, design (top right) and field intensity in an array of waveguide.

Functionality is determined by the core layer

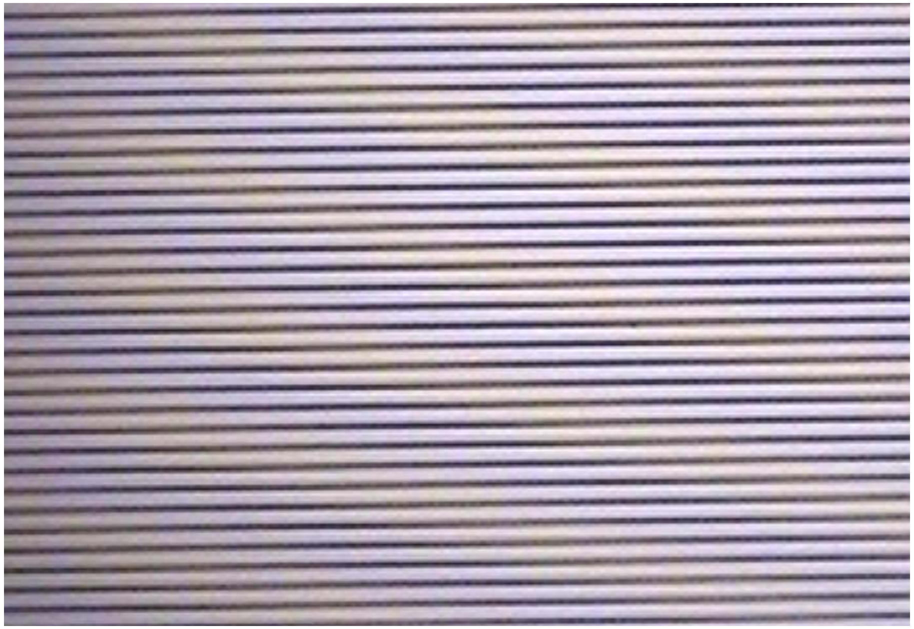
Photonic components

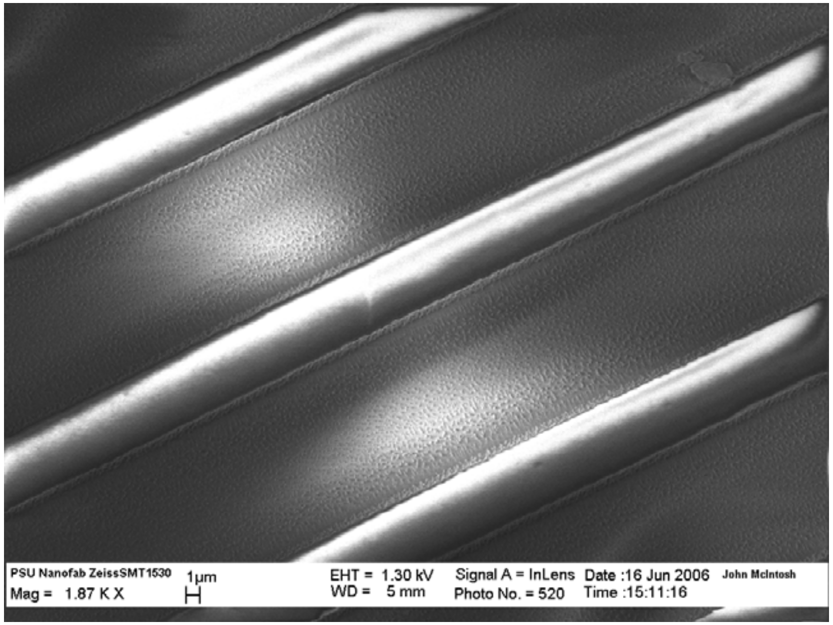


Demonstration of photonic components from dendrimer

Fabricated at Penn State University Nanofab Facility

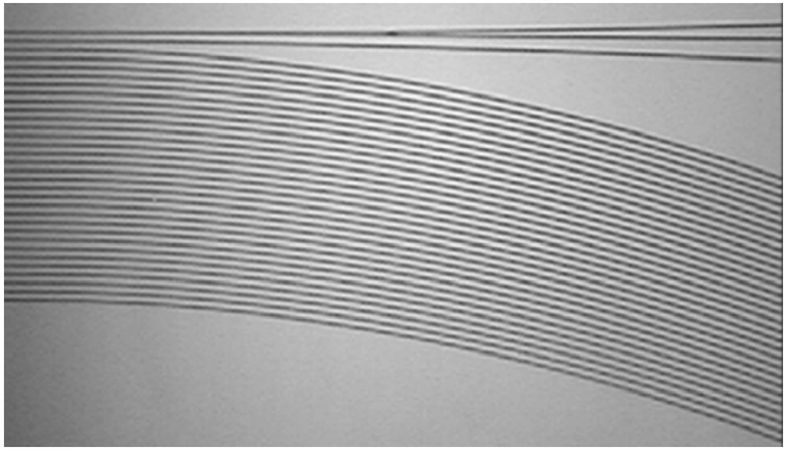
Waveguide Array



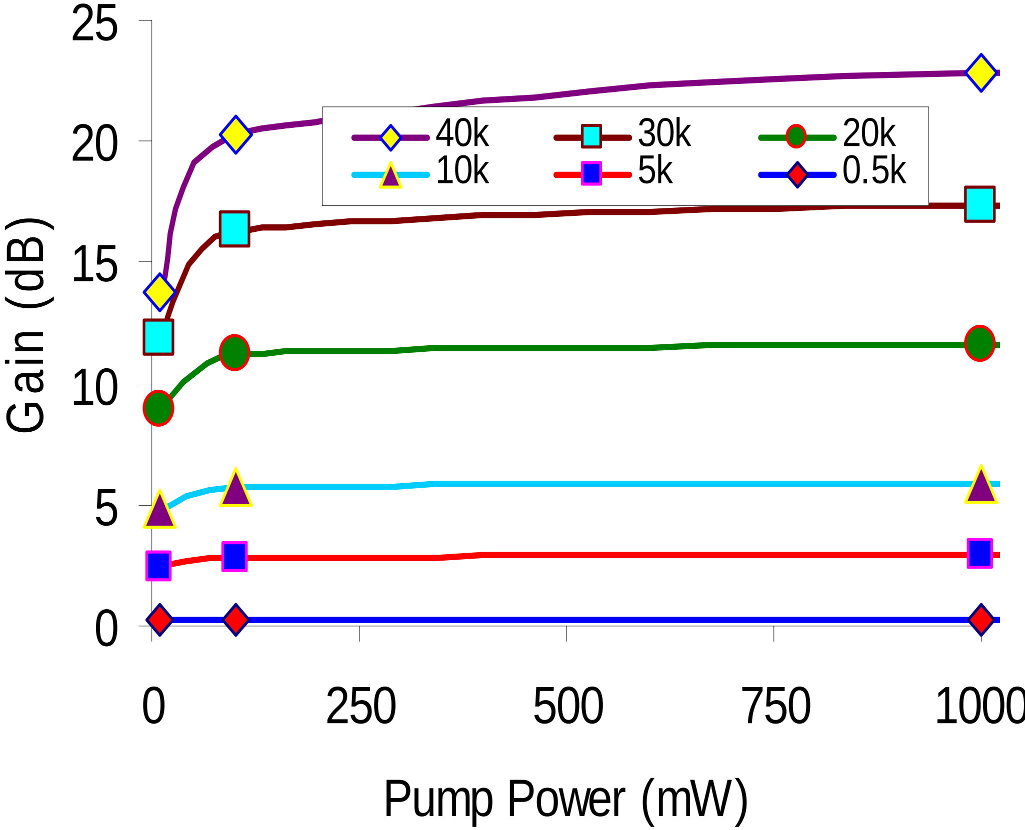


Left: Photomicrograph of an array of waveguide from dendrimer.
Right: SEM micrograph showing the ridges that forms the core of waveguide.

Optical amplifier

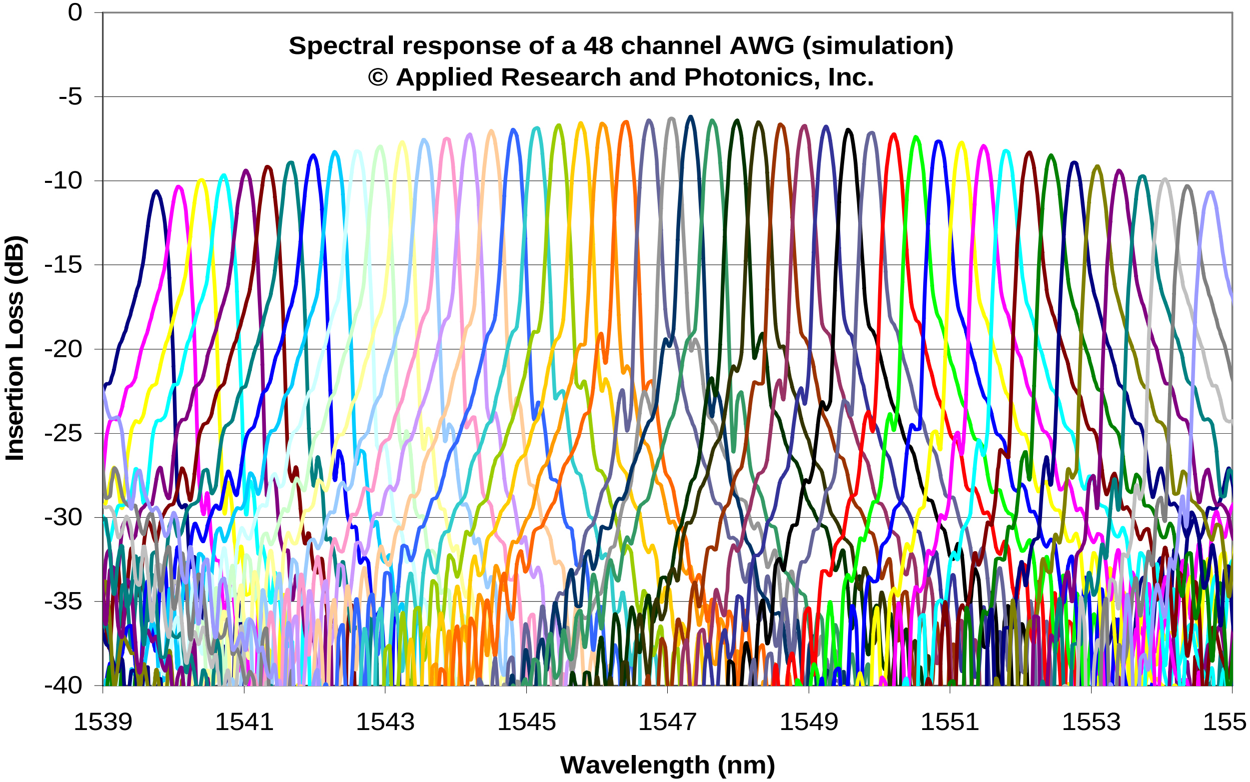


Close-up of fabricated amplifier section



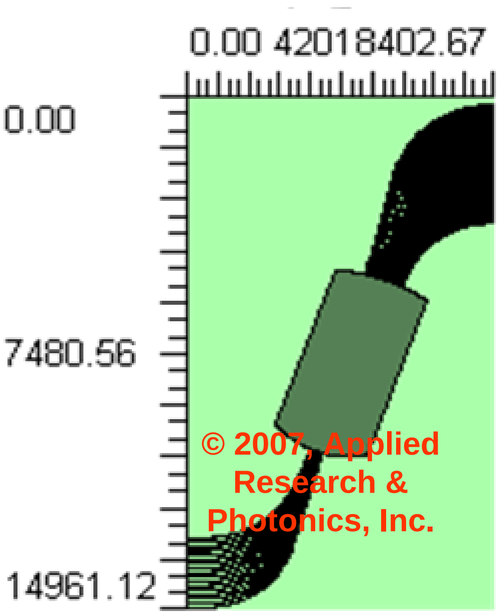
Simulation of erbium doped dendrimer waveguide amplification

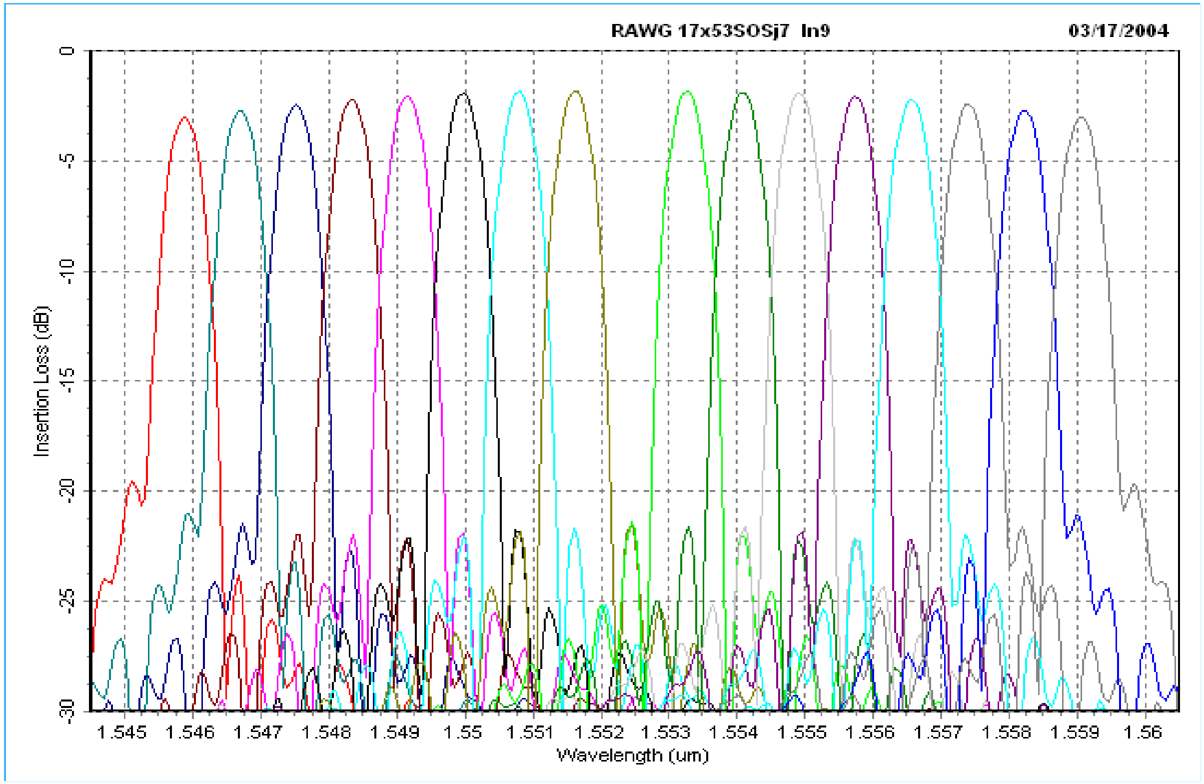
Arrayed Waveguide Grating



A 48 channel TAWG and its spectral response designed from dendrimer

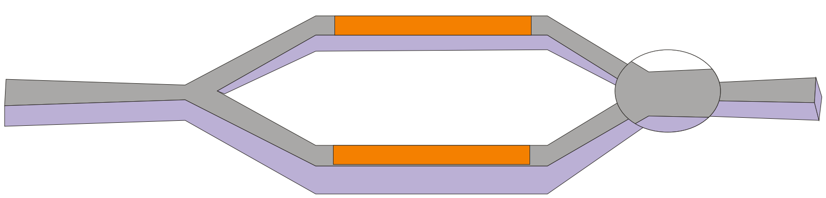
RAWG

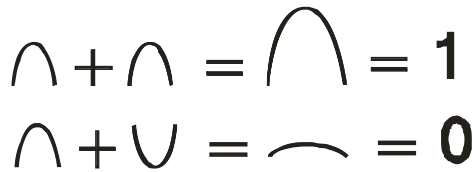


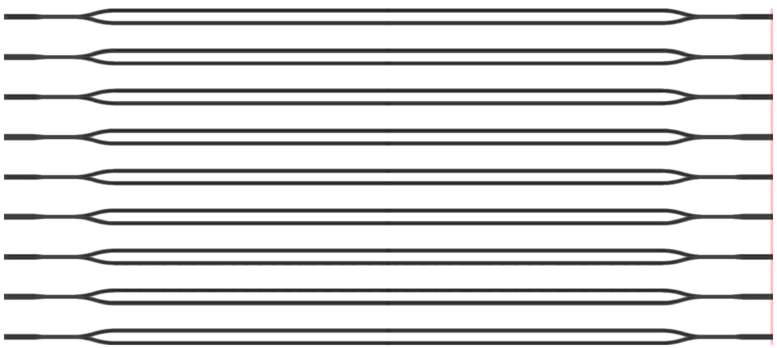


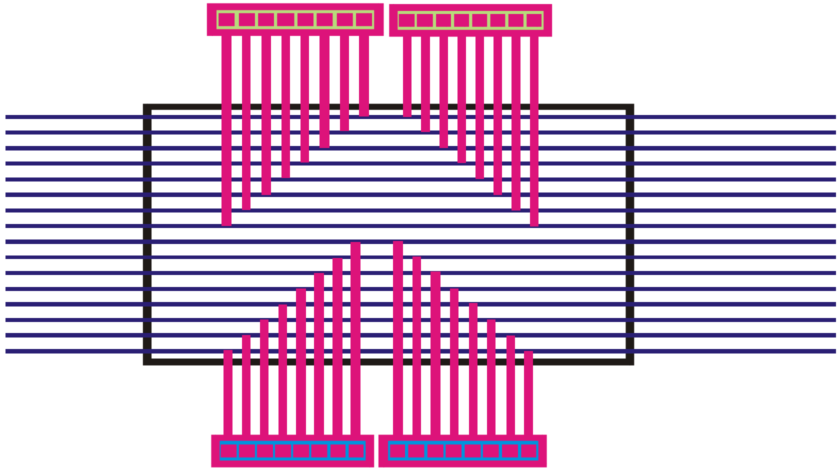
A 16 channel RAWG and its spectral response.

Modulator



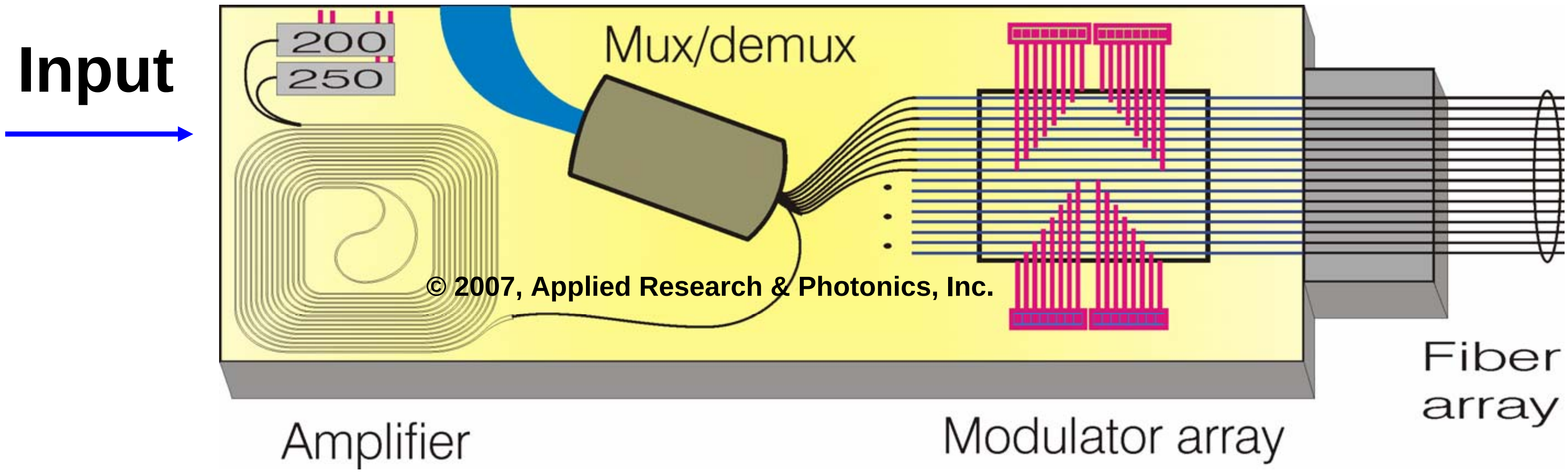






- **Here the waveguide core is made from EO dendrimer**
- **Electrodes are added to drive the modulator**
- **Basic element for sensing**

nPIC



Depending on the configuration

- **Optical communication node**
- **Multi-channel sensor network**

Summary

- Dendrimer is a workhorse matl. for photonics.
- Electro-optic rectification is not limited by THz emission saturation or by heat dissipation → power scalability.
- > 100 mW per chip can be generated from EO dendrimer waveguide array.
- Applications in molecular spectroscopy, diagnosis, security, screening, …
- Active and passive photonic components can be integrated via monolithic fabrication
- Opportunities for collaboration.