Developments and Applications of Optical Parametric Devices

Jing-Yuan Zhang (张景园)

Title of Lecture #1:
Development of Optical Parametric Devices as Tunable Sources
Time: 2:30-4:45 PM, Tue., August 1, 2006

Title of Lecture #2:
Applications of OPA in Ultra-sensitive Detection and Other Non-academic Fields
Time: 2:30-4:45 PM, wed., August 2, 2006
Development of Optical Parametric Devices as Tunable Sources

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August 1, 2006
Outline

1. Why do nonlinear-optical effects occur
2. Maxwell's equations in a medium
3. Second-harmonic generation
4. Sum- and difference-frequency generation
5. Second-order and higher-order nonlinear optics
6. Phase-matching and Conservation laws for photon
7. Optical parametric processes as a tunable source
8. Current status of optical parametric devices
9. Application of parametric devices in laser TV
Why do nonlinear-optical effects occur?

- Recall that, in normal linear optics, a light wave acts on a molecule, which vibrates and then emits its own light wave that interferes with the original light wave.

We can also imagine this process in terms of the molecular energy levels, using arrows for the photon energies:
Why do nonlinear-optical effects occur? (continued)

Now, suppose the irradiance is high enough that many molecules are excited to the higher-energy state. This state can then act as the lower level for additional excitation. This yields vibrations at all frequencies corresponding to all energy differences between populated states.

![Molecular energy levels diagram](image)
The electric polarization becomes nonlinear at high E-field:

\[ P(t) = \varepsilon_0 \chi^{(1)} E(t) + \chi^{(2)} E^2(t) + \chi^{(3)} E^3(t) + ... \]

\[ P(\omega) = \varepsilon_0 \sum \chi_{ij}^{(1)} E(\omega_m) + \sum \chi_{ijk}^{(2)} E_j(\omega_m) E_k(\omega_n) \]
\[ + \sum \chi_{ijkl}^{(3)} E_j(\omega_m) E_k(\omega_n) E_l(\omega_o) + ... \]

E-field of a high-power laser pulse:

\[ I = 10-50 \text{ GW/cm}^2 \Rightarrow E = 3-6 \times 10^8 \text{ V/m} \]
Second-order nonlinear-optical effects

Second Harmonic Generation (SHG)
Sum Frequency Generation (SFG)
Electro-Optics (E-O)
Optical Rectification (OR)
Difference Frequency Generation (DFG)
Optical Parametric Generation/Amplification (OPG/OPA)
Term $\sum \chi_{ijk}^{(2)}(\omega_m, \omega_n) E_j(\omega_m) E_k(\omega_n)$ is responsible to all of the three-wave second order of nonlinear optical effects, including second harmonic generation (SHG: $\omega + \omega = 2\omega$), sum-frequency generation (SFG: $\omega_1 + \omega_2 = \omega_3$), difference frequency generation (DFG: $\omega_1 - \omega_2 = \omega_3$), or optical parametric processes (OPG/OPA and OPO: $\omega_1 = \omega_2 + \omega_3$):

$\omega_1$  \rightarrow \text{Nonlinear Optical medium}  \rightarrow \omega_1 + \omega_1 = 2\omega_1$

$\omega_2$  \rightarrow \text{Nonlinear Optical medium}  \rightarrow \omega_1 + \omega_2 = \omega_3$

$\omega_1 - \omega_2 = \omega_3$
Maxwell Eq. for Second Harmonic Generation (SHG)

Equations for SHG:

\[
\begin{align*}
\left( \frac{\partial}{\partial z} + \frac{1}{v_{g1}} \frac{\partial}{\partial t} \right) E_1 &= -i\chi^{(2)} \frac{\omega_1^2}{2c^2k_1} E_2^* E_3 e^{i\Delta k \cdot z} \\
\left( \frac{\partial}{\partial z} + \frac{1}{v_{g2}} \frac{\partial}{\partial t} \right) E_2 &= -i\chi^{(2)} \frac{\omega_2^2}{2c^2k_2} E_1^* E_3 e^{i\Delta k \cdot z} \\
\left( \frac{\partial}{\partial z} + \frac{1}{v_{g3}} \frac{\partial}{\partial t} \right) E_3 &= -i\chi^{(2)} \frac{\omega_3^2}{2c^2k_3} E_1 E_2 e^{-i\Delta k \cdot z}
\end{align*}
\]

where:

- \( k_i \) = wave vector of \( i^{th} \) wave
- \( \Delta k = k_1 + k_2 - k_3 \)
- \( v_{g_i} \) = group velocity of \( i^{th} \) wave

The solutions for \( E_1 \) and \( E_2 \) involve exponential gain!
Phase-matching in second-harmonic generation

How does phase-matching affect SHG? It’s a major effect, another important reason you just don’t see SHG—or any other nonlinear-optical effects—every day.
Phase-matching second-harmonic generation using birefringence

Birefringent materials have different refractive indices for different polarizations. Ordinary and extraordinary refractive indices can be different by up to ~0.1 for SHG crystals.

We can now satisfy the phase-matching condition.

Use the extraordinary polarization for $\omega$ and the ordinary for $2\omega$.

$$n_o(2\omega) = n_e(\omega)$$

$n_e$ depends on propagation angle, so we can tune for a given $\omega$. Some crystals have $n_e < n_o$, so the opposite polarizations work.
Noncollinear SHG phase-matching

\[ \vec{k} = k \cos \theta \hat{\mathbf{z}} - k \sin \theta \hat{\mathbf{x}} \rightarrow \]

\[ \vec{k}' = k \cos \theta \hat{\mathbf{z}} + k \sin \theta \hat{\mathbf{x}} \rightarrow \]

\[ \vec{k}_{pol} = \vec{k} + \vec{k}' = 2k \cos \theta \hat{\mathbf{z}} \]

\[ \Rightarrow k_{pol} = 2 \frac{\omega}{c_0} n(\omega) \cos \theta \]

But:

\[ k_{sig} = \frac{2\omega}{c_0} n(2\omega) \]

So the phase-matching condition becomes:

\[ n(2\omega) = n(\omega) \cos \theta \]
First demonstration of second-harmonic generation


Figure 12.1. Arrangement used in the first experimental demonstration of second-harmonic generation [1]. A ruby-laser beam at $\lambda = 0.694 \, \mu m$ is focused on a quartz crystal, causing the generation of a (weak) beam at $\frac{1}{2}\lambda = 0.347 \, \mu m$. The two beams are then separated by a prism and detected on a photographic plate.

The second-harmonic beam was very weak because the process was not phase-matched.
First demonstration of SHG: the data

The actual published results...

Note that the very weak spot due to the second harmonic is missing. It was removed by an overzealous Physical Review Letters editor, who thought it was a speck of dirt.
SHG efficiency

The second-harmonic field is given by:

$$E^{2\omega}(L,t) = -i \frac{\mu_0 \omega^2 L}{2k} P \exp(i\Delta k L/2) \text{sinc}(\Delta k L/2)$$

The irradiance will be:

$$I^{2\omega} = \frac{\eta_0 \omega^2 (\chi^{(2)})^2 (I^{\omega})^2 L^2}{2c_0^2 n^3} \text{sinc}^2(\Delta k L/2)$$

Dividing by the input irradiance to obtain the SHG efficiency:

$$\frac{I^{2\omega}}{I^{\omega}} = \frac{2\eta_0 \omega^2 d^2 I^{\omega} L^2}{c_0^2 n^3}$$

Substituting in typical numbers:

$$\frac{I^{2\omega}}{I^{\omega}} \approx [5 \times 10^{-8}/W] I^{\omega} L^2$$

Take $\Delta k = 0$

d $\propto \chi^{(2)}$, and includes crystal additional parameters.
Sinusoidal dependence of SHG intensity on length

Large $\Delta k$

Small $\Delta k$

Notice how the intensity is created as the beam passes through the crystal, but, if $\Delta k$ isn’t zero, newly created light is out of phase with previously created light, causing cancellation.
Serious second-harmonic generation

Frequency-doubling KDP crystals at Lawrence Livermore National Laboratory

These crystals convert as much as 80% of the input light to its second harmonic. Then additional crystals produce the third harmonic with similar efficiency!

These guys are serious!
Even higher intensities!

National Ignition Facility (under construction)

192 shaped pulses; 1.8 MJ total energy
Even Higher Intensities!

National Ignition Facility
(under construction)

192 shaped pulses
10.4 kJ per beam in UV (done)
21 kJ per beam in IR (done)
>1.8 MJ total energy (planned)
Pulses 0.2 to 25 ns in length
Phase-matching bandwidth

Recall that the intensity out of an SHG crystal of length $L$ is:

$$I_{\text{sig}}(L) \propto (L / \lambda)^2 \text{sinc}^2(\Delta k L / 2)$$

where:

$$\Delta k(\lambda) = \frac{4\pi}{\lambda} [n(\lambda) - n(\lambda / 2)]$$

Phase-matching only works exactly for one wavelength, say $\lambda_0$. Since ultrashort pulses have lots of bandwidth, achieving approximate phase-matching for all frequencies is a big issue.

The range of wavelengths (or frequencies) that achieve approximate phase-matching is the phase-matching bandwidth.
Group-velocity mismatch of SHG of ultra-short lasers

Inside the crystal the two different wavelengths have different group velocities.

Define the Group-Velocity Mismatch (GVM):

\[ GVM \equiv \frac{1}{v_g(\lambda_0/2)} - \frac{1}{v_g(\lambda_0)} \]

As the pulse enters the crystal:
- Second harmonic created just as pulse enters crystal (overlaps the input pulse)

As the pulse leaves the crystal:
- Second harmonic pulse lags behind input pulse due to GVM
Group-velocity mismatch (GVM)

Calculating GVM:

\[ v_g(\lambda) = \frac{c_0/n(\lambda)}{1 - \frac{\lambda}{n(\lambda)} n'(\lambda)} \]

So:

\[ \frac{1}{v_g(\lambda)} = \frac{n(\lambda)}{c_0} \left[ 1 - \frac{\lambda}{n(\lambda)} n'(\lambda) \right] \]

\[ GVM \equiv \frac{1}{v_g(\lambda_0/2)} - \frac{1}{v_g(\lambda_0)} \]

\[ = \frac{n(\lambda_0/2)}{c_0} \left[ \frac{\lambda_0/2}{n(\lambda_0/2)} \right] - \frac{n(\lambda_0)}{c_0} \left[ \frac{\lambda_0}{n(\lambda_0)} \right] \]

But we only care about GVM when \( n(\lambda_0/2) = n(\lambda_0) \)

\[ GVM = \frac{\lambda_0}{c_0} \left[ n'(\lambda_0) - \frac{1}{2} n'(\lambda_0/2) \right] \]
Group-velocity mismatch lengthens the SH pulse.

Assuming that a very short pulse enters the crystal, the length of the SH pulse, $\delta t$, will be determined by the difference in light-travel times through the crystal:

$$\delta t = \frac{L}{v_g(\lambda_0 / 2)} - \frac{L}{v_g(\lambda_0)} = L \frac{GVM}{\tau_p}$$

We always try to satisfy: $L \frac{GVM}{\tau_p} \ll \tau_p$
Group-velocity mismatch pulse lengthening of ultra-short laser pulses

Second-harmonic pulse shape for different crystal lengths:

\[ L_D \equiv \frac{\tau_p}{GVM} \]

\( L_D \) is the crystal length that doubles the pulse length.

It’s best to use a very thin crystal. Sub-100-micron crystals are common for fs-laser.
### Group-velocity mismatch numbers

<table>
<thead>
<tr>
<th>crystal</th>
<th>$\lambda$ [nm]</th>
<th>$\theta$ [$^\circ$]</th>
<th>$(v_2^{-1} - v_1^{-1})$ [fs/mm]</th>
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<td>KDP</td>
<td>550</td>
<td>71</td>
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<td>LiIO$_3$</td>
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<td></td>
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<tr>
<td></td>
<td>1500</td>
<td>20</td>
<td>5</td>
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</table>
Group-velocity mismatch limits bandwidth.

Let's compute the second-harmonic bandwidth due to GVM.
Take the SH pulse to have a Gaussian intensity, for which \( \delta t \delta \nu = 0.44 \).
Rewriting in terms of the wavelength,

\[
\delta t \delta \lambda = \delta t \delta \nu \frac{d\nu}{d\lambda} = 0.44 \frac{d\nu}{d\lambda} = 0.44 \frac{\lambda^2}{c_0}
\]

where we've neglected the minus sign since we're computing the bandwidth, which is inherently positive. So the bandwidth is:

\[
\delta \lambda_{\text{FWHM}} \approx \frac{0.44 \lambda_0^2}{\delta t c_0} = \frac{0.44 \lambda_0^2}{L \text{ GVM}}
\]

Calculating the bandwidth by considering the GVM yields the same result as the phase-matching bandwidth!
Alternative method for phase-matching: periodic poling

Recall that the second-harmonic phase alternates every coherence length when phase-matching is not achieved, which is always the case for the same polarizations—whose nonlinearity is much higher.

Periodic poling solves this problem. But such complex crystals are hard to grow and have only recently become available.
Phase-matching = Conservation laws for photons in nonlinear optics

Adding the frequencies:

\[ \omega_1 + \omega_2 + \omega_3 - \omega_4 + \omega_5 = \omega_{\text{sig}} \]

is the same as energy conservation if we multiply both sides by \( \hbar \):

\[ \hbar \omega_1 + \hbar \omega_2 + \hbar \omega_3 - \hbar \omega_4 + \hbar \omega_5 = \hbar \omega_{\text{sig}} \]

Adding the \( k \)'s conserves momentum:

\[ \vec{k}_1 + \vec{k}_2 + \vec{k}_3 - \vec{k}_4 + \vec{k}_5 = \vec{k}_{\text{sig}} \]

\[ \hbar \vec{k}_1 + \hbar \vec{k}_2 + \hbar \vec{k}_3 - \hbar \vec{k}_4 + \hbar \vec{k}_5 = \hbar \vec{k}_{\text{sig}} \]

So phase-matching is equivalent to conservation of energy and momentum!
Difference-Frequency Generation: Optical Parametric Generation, Amplification, Oscillation

Difference-frequency generation takes many useful forms.

Parametric Down-Conversion (Difference-frequency generation)

Optical Parametric Generation (OPG)

Optical Parametric Amplification (OPA)

Optical Parametric Oscillation (OPO)

By convention: \( \omega_{\text{signal}} > \omega_{\text{idler}} \)
Maxwell Eq. for Optical **Parametric Amplification**

Equations are just about identical to those for SHG:

\[
\begin{align*}
\left( \frac{\partial}{\partial z} + \frac{1}{v_{g1}} \frac{\partial}{\partial t} \right) E_1 &= -i \chi^{(2)} \left( \frac{\omega_1^2}{2c^2 k_1} \right) E^*_2 E_3 e^{i\Delta k \cdot z} \\
\left( \frac{\partial}{\partial z} + \frac{1}{v_{g2}} \frac{\partial}{\partial t} \right) E_2 &= -i \chi^{(2)} \left( \frac{\omega_2^2}{2c^2 k_2} \right) E^*_1 E_3 e^{i\Delta k \cdot z} \\
\left( \frac{\partial}{\partial z} + \frac{1}{v_{g3}} \frac{\partial}{\partial t} \right) E_3 &= -i \chi^{(2)} \left( \frac{\omega_3^2}{2c^2 k_3} \right) E_1 E^*_2 e^{-i\Delta k \cdot z}
\end{align*}
\]

where:

- \( k_i \) = wave vector of \( i^{th} \) wave
- \( \Delta k = k_1 + k_2 - k_3 \)
- \( v_{gi} \) = group velocity of \( i^{th} \) wave

The solutions for \( E_1 \) and \( E_2 \) involve exponential gain!

OPA’s etc. are ideal uses of ultrashort pulses, whose intensities are high.
Gain of OPA

\[ G = \frac{I_s(L)}{I_s(0)} = \frac{1}{4} e^{2\Gamma L} \quad \text{when } \Delta K = 0 \]

where

\[ \Gamma^2 = \frac{(8\pi^2 d_{\text{eff}}^2 I_p)}{(n_i n_s n_p \lambda_i \lambda_s \lambda_p \varepsilon_\text{o} C)} \]
Phase-matching curves a BBO-based OPA by angle-tuning (type I: o+o→e and type II: o+e→e) pumped at 355 nm.
Non-critical Phase-matching: T-tuning

We can vary the crystal angle in the usual manner, or we can vary the crystal temperature (since $n$ depends on $T$).
Dye laser as a tunable source
Optical configuration of

Optical Parametric Oscillator/Amplifier
Optical Parametric Generation/Amplification and Oscillation (OPG/OPA and OPO)

Nanosecond OPO

Key Features

- Tunable output from 410 nm to 2 μm with several linewidth and energy options
- Master Oscillator/Power Oscillator design for highest conversion efficiency and mode quality
- Active feedback loops ensure day-to-day peak performance
- Automated control electronics
- A single set of proprietary dichroic mirrors separate the signal and idler beams across the entire tuning range
- Beam lock technique provides active stabilization of beam pointing and UV energy
- Integral frequency doubler (FDO) bolts directly to the MOPO baseplate
Optical configuration of picosecond-OPA

PS-YAG  SHG  THG  DM1  BD  HM1-3

HM-4  BBO-1  BBO-2  DM2-3  BBO-3  BBO-4
Key Features

• Tunable from 1.1 \( \mu \text{m} \) to 3.0 \( \mu \text{m} \) with no tuning hole in output
• Optional harmonic and difference frequency-mixing accessories extend tuning range from <300 nm to >10 \( \mu \text{m} \)
• Sum frequency mixing option
• Pulse-to-pulse stability with kHz repetition rates
• Type II phase matching of the OPA crystal (BBO) produces near transform limited output and allows tuning through degeneracy point
• Two-stage amplifier design with unique pump beams for each amplification stage
• Sub-50 fs and sub-90 fs pulse widths available
• Picosecond option with <25 cm^{-1} linewidth
• Capable of dual OPA operation with single Ti:sapphire regenerative amplifier
• Operation with fs or ps output or with different pumping energies
Recent development of OPG/OPA in the ultra-short pulse duration


**~5-fs OPA with a bandwidth of ~600-800 nm, T. Kobayashi’s group, Optics Letters, April, 2002**

White-light (bandwidth of 700 nm) OPA---potential for <3-fs
NOPIA specs

<table>
<thead>
<tr>
<th>Modification</th>
<th>Tuning ranges (nm)</th>
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<tr>
<td>TOPAS-white</td>
<td>490-750, 850-1000</td>
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<tr>
<td>TOPAS-white-SH</td>
<td>245-375, 425-490</td>
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<tr>
<td>TOPAS-white-IR</td>
<td>490-750, 850-1000</td>
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<td>TOPAS-white-IR-SH</td>
<td>245-375, 425-490</td>
</tr>
<tr>
<td></td>
<td>(SH of Signal)</td>
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<td>(Idler)</td>
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</table>

PERFORMANCE SPECIFICATIONS WITH 0.5 mJ PUMP PULSES

**SIGNAL OUTPUT (all modifications)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuning range</td>
<td>490 - 750 nm</td>
</tr>
<tr>
<td></td>
<td>850 - 1000 nm</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>≥ 30 μJ @ 550 nm</td>
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<tr>
<td></td>
<td>≥ 20 μJ @ 700 nm</td>
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<tr>
<td>Pulse duration, sech²</td>
<td>≤ 20 fs @ 530 - 720 nm</td>
</tr>
<tr>
<td></td>
<td>≤ 60 fs @ 490 - 530 nm</td>
</tr>
<tr>
<td></td>
<td>≤ 60 fs @ 720 - 1000 nm</td>
</tr>
<tr>
<td>Energy instability</td>
<td>≤ 1.5% rms - 5% rms (depending on the wavelength and the input stability)</td>
</tr>
<tr>
<td>Instability of pulse duration</td>
<td>≤ 2% rms</td>
</tr>
<tr>
<td>Pre-pulse contrast</td>
<td>≤ 10⁻³</td>
</tr>
<tr>
<td>Spatial profile</td>
<td>Super-gaussian, M²≤1.5</td>
</tr>
</tbody>
</table>
Commercial All Solid Optical Parametric Systems as Tunable Sources
Optical Parametric Generation of IR

Recent results using the nonlinear medium, periodically poled RbTiOAsO$_4$

Recent development of OPG/OPA in the tuning range:

1. Extension to UV (266-nm-pumped CLBO)
   

   Tuning range: 347nm—1137nm
   Optical efficiency: 11%

2. Extension to Far-IR & THZ (1064-pumped GaSe)

   C.-W. Chen, Y.-K. Hsu, J. Y. Huang, C.S. Chang, C.-L. Pan, J.-Y. Zhang, "Intense Picosecond Infrared Pulses Tunable from 2.4 μm to 38 μm for Nonlinear Optics Application", (Presented at JQEC and CLEO-Pacific-Rim, paper CFI3-1, Tokyo, Japan, July 11-15, 2005)


   C.-W. Chen, Y.-K. Hsu, J. Y. Huang, C.S. Chang, C.-L. Pan, J.-Y. Zhang, “Parametric gain dominated picosecond infrared light source tuning from 2.4 μm to 38 μm by difference frequency generation in GaSe”, (Optics Express, to be published)
Terahertz radiation ("T-rays").

THz light has very unusual absorption properties.
Generation of free-space THz pulses using ultrashort pulses

A fs pulse induces conductivity in a biased photoconductive switch. When the pulse is on, current flows. Accelerating charges emit light.
THz yields a time-domain spectrometer

Simply measuring the THz spectrum before and after a sample tells us its absorption spectrum in the THz range.

THz has been used to measure species in a flame (Grischkowski and coworkers).
THz image of a semiconductor integrated circuit

THz sees the metal leads through the plastic packaging.
~ 0.25 millimeter spatial resolution
Useful for fault detection, delamination
Visible image of human tooth  

Terahertz image of cavity in human tooth

Cavity

Image composed from absorption data
Tumors appear to have different THz absorption properties from normal tissue.
Plant is allowed to dry somewhat, and then watered. As the leaf rehydrates, THz transmission decreases. Changes smaller than 1% are detectable.
THz (0.1-10 THz) Generation by Difference Frequency Generation (DFG)

THz generation by optical rectification

1.5 kw, 0.7-2.0 THz, ps, Daniel. F. Gordon et al. Optics Express, 14, 6815, 2006

Diagram of the THz generation system:
- OSC
- Stretcher
- Regen
- M1
- Slits
- L1
- M2
- Amp
- Compressor
- λ/2 GaSe
- G1
- G2
- Bolometer
Effect of Er-doping on THz-DFG in GaSe crystal

Optical Configuration of DFG for generating high-power, picosecond FIR/THz
Phase matching curve for Type-I GaSe crystal pumped at 1064-nm

![Graph showing phase matching curve for Type-I GaSe crystal]
Fig. 2. X-Ray rocking curves of the diffraction peak from the (008) plane of the pure GaSe and 0.5% Er:GaSe crystals.
Absorption and doping in GaSe

Infrared transmission spectra of the pure and 0.5% Er:GaSe crystals. Inset, optical transmission spectra of the pure and 0.5% Er:GaSe crystals at near infrared region.
Generation of Tunable Far-IR in GaSe

![Graph showing pulse energy vs. output wavelength for pure GaSe and 0.2% and 0.5% Er:GaSe samples.]

- □ — pure GaSe
- ○ — 0.2% Er:GaSe
- △ — 0.5% Er:GaSe
Doping and Optical Efficiency in DFG

![Graph showing the relationship between Energy/Pulse (μJ) and Efficiency (%). Two lines are plotted, one for 0.5% Er:GaSe and another for pure GaSe. The graph includes data points for both types of materials.](image)
Why Thin and Large Screen Laser-TVs?
Demands for large screen TV has been increasing and only laser-TV can provide >80” screen

![Large Screen (>40”) Industry Sales (U.S.)]
Consumer’s needs are the fuel of larger TVs

Sit closer than you think and be immersed in the picture.

Recommended Viewing Distance:

- 480p
  - 19 feet
  - (Diagonal x 3.5=19’)
- 720p
  - 12 feet
  - (Diagonal x 2.3=12’)
- 1080p
  - 8 feet
  - (Diagonal x 1.5=8’)

52” – 6 feet
57” – 7 feet
65” – 8 feet
73” – 9 feet
Advantages of Laser TV
--- RGB Generation

Lasers have long been recognized for their potential as illumination sources for projection applications due to their wide color gamut and high light energy efficiency.

Advantages of laser TV:
• Laser enables thin, sculpted, modern look
• Laser enables large, lightweight, efficient design
• Laser provides the most precise light source available
• Widest range of colors of any display technology
• Color gamut (>90%) 1.8x standard LCD (58%) displays 1.3x NTSC(78%), and 3.3x plasma (30%) displays
• Pure deep colors (Ultra High Color Intensity)
• Laser enables unrivaled picture quality
• Laser enables large-screen
Chromaticity diagram according to CIE 1931, taken from efg's Computer Lab, page on chromaticity diagrams, with friendly permission from Earl F. Glynn. His webpage contains more information on different kinds of chromaticity diagrams.
Advantages of Laser TV

激光显示与传统电视色域的比较
Schematics of RGB Laser-TV
Optical configuration for OPA-based RGB generation

Laser-I @1.06 μm

OPO@1.50 μm

Laser-II @1.34 μm

SHG

SFG

SHG

SFG

532 nm

628 nm

447 nm
A very thin 100-inch Laser TV
100", thin wall-hanging laser-TV
Laser-based projection system displays high definition television (HDTV) images on 20 ft. screen. (Courtesy of COLOR)
Using DPSS and OPO technology for RGB generation

* Modulation: Reflective liquid crystal display technology
* Pump source: Near-IR by DPSS in vanadate (Nd:YVO4) laser
* RGB generation:
  (a) OPO pumped by DPSS at 1.0-μm to generate 1.5-μm beam;
  (b) SFG of 1.5-μm beam with 1.0-μm to generate pulsed 628 nm emission with an average power of 10 W
  (c) SHG of vanadate (Nd:YVO4) laser capable of producing 13 W at 532 nm.
  (d) A second Nd:YVO4 laser operating at third harmonic (SHG+SFG) produces 7 W of output at 447 nm
* Brightness: exceeds 10,000 lumens, reduced by 2/3 as it passes through the projection system,
* Effective luminance: 3000 ANSI lumens at the screen
* Resolution: 1600 x 1200 DPI;
* Contrast ratio: as high as 1700:1 (500:1 for lamp-based systems)
* Video bandwidth: as high as 150 MHz

Data from COLOR’s Color-Vision System
中科院物理所许祖彦院士小组的研究成果
(2004-2005)

——参加国家十五重大科技成就展、上海国际工业博览会、
国家科技创新成就展
——2005年11月获上海国际工业博览会创新奖
最新(2006.5)的研究成果
关键技术突破，达到实用化水平

Recent Specification:
R: 8 W (21.7 W)@660nm
G: 3.5 W (30W)@532nm
B: 5 W (6.3 W)@440nm
Size: 200-inch (4mx3m)
Brightness: 1500 lumen
## 中科院激光电视与已有技术的比较

与国际激光显示采用的色域的比较（计算结果）

<table>
<thead>
<tr>
<th>单 位</th>
<th>红光 (nm)</th>
<th>绿光 (nm)</th>
<th>蓝光 (nm)</th>
<th>色域（% NTSC）</th>
<th>覆盖率（%）</th>
</tr>
</thead>
<tbody>
<tr>
<td>中国科学院</td>
<td>669</td>
<td>515</td>
<td>440</td>
<td>253.4</td>
<td>79.2</td>
</tr>
<tr>
<td>日本 SONY</td>
<td>642</td>
<td>532</td>
<td>457</td>
<td>214.4</td>
<td>67.0</td>
</tr>
<tr>
<td>德国 LDT</td>
<td>628</td>
<td>532</td>
<td>446</td>
<td>209.4</td>
<td>65.4</td>
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<tr>
<td>美国 LPC</td>
<td>656</td>
<td>532</td>
<td>457</td>
<td>221.7</td>
<td>69.3</td>
</tr>
<tr>
<td>美国 Q-peak</td>
<td>628</td>
<td>524</td>
<td>449</td>
<td>215.5</td>
<td>67.3</td>
</tr>
<tr>
<td>瑞士 ETH</td>
<td>603</td>
<td>515</td>
<td>450</td>
<td>169.0</td>
<td>54.8</td>
</tr>
</tbody>
</table>

本成果色域测量结果：
色域覆盖率：73.6%  色域：235.1% NTSC
Laser display at US Air force
Flight simulators at US Air Force
Summary of Optical Parametric Devices

- **Tuning range of OPO/OPG/OPA**:
  - **Near/mid-IR**: 1.2-8.5 μm (1064-nm pumped LiNbO₃, AgGaS₂) J. Y. Zhang et al., 1990, J. Y. Zhang, et al. 1995
  - **Far-IR/THz**: 0.2-10 THz, 200W at 1.5 THz ns W. Shi, Y. J. Ding et al, Appl. Phys. Lett. 8.0, 3889, 2002);
    - 4-10 THz, 5KW, ps. C. W. Chen and J. Y. Zhang et al, 2005 CLEO; Optics Express, 14, 5484, 2006;
    - 1.5 kw, 0.7-2.0 THz, ps. Daniel. F. Gordon et al. Optics Express, 14, 6815, 2006

- **Bandwidth of OPO/OPG/OPA**:
  - **ns-OPO**: 0.1-1.0 cm⁻¹;
  - **ps-OPG/OPA**: 1-10 cm⁻¹; (J. Y. Zhang, 1990)
  
  We have increased to 13,400 cm⁻¹ (J. Y. Zhang et al., 2004)

- **Pulse duration of OPO/OPG/OPA**:
  - **Nano-second OPO** (3-5 ns)
  - **Pico-second OPG/OPA** (10-20 ps)
  
  Potentially can be reduced to ~2-3 fs

• J. Y. Zhang, J. Y. Huang and Y. R. Shen, "Picosecond optical parametric amplification in lithium triborate", Applied Physics Letters, 58, 213 (1990);


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• D. Zhang, Y. F. Kong and J. Y. Zhang, “Optical parametric properties of 532-nm-pumped BBO near the infrared absorption edge”, Optics Communications, 184, 485-491 (2000);


• Chao-Kuei Lee, Jing-Yuan Zhang, J. Y. Huang and Ci-Ling Pan, “Generation of femtosecond laser pulses tunable from 380 nm to 465 nm via cascaded nonlinear optical mixing in a noncollinear optical parametric amplifier with a type-I phase matched BBO crystal”, Optics Express 11, 1702-1708 (2003);


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