NAG1-1968 Final Report

Investigation of a Novel 940-nm Laser Transmitter Incorporating an Optical Parametric Amplifier

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Outline

- Rationale
- Objective
- Approach
- Experimental results
- System issues
- Conclusion

Rationale

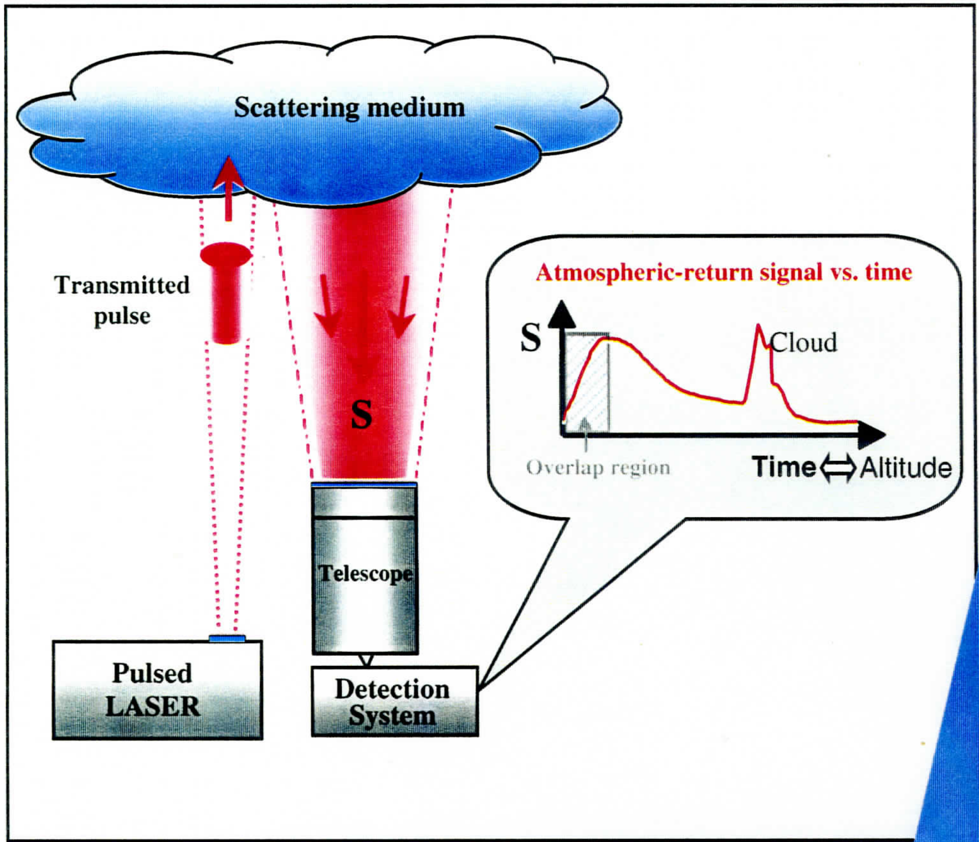
NASA and lidar-community strongly desire a 940-nm laser transmitter.

Application:
To measure atmospheric distribution of water vapor throughout the atmosphere (inc. upper trop./lower strat.) using the differential absorption lidar (DIAL) technique.

Requirements:
Narrow-band tunable pulsed laser ($\Delta\lambda < 1$ pm)
Efficient, compact and robust.

DIAL Concept

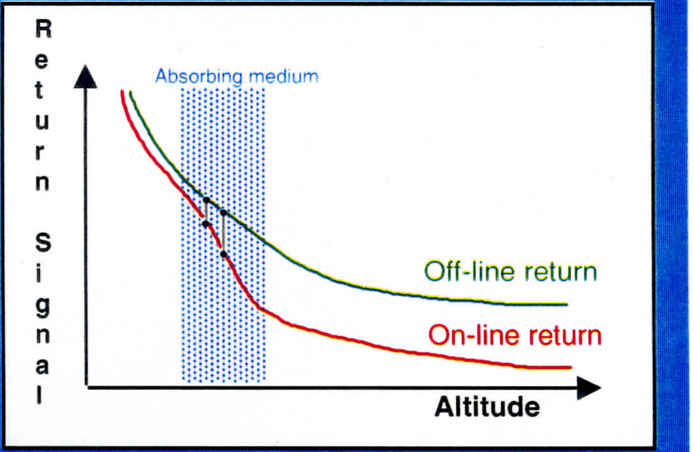
940-nm OPA



Basic lidar system

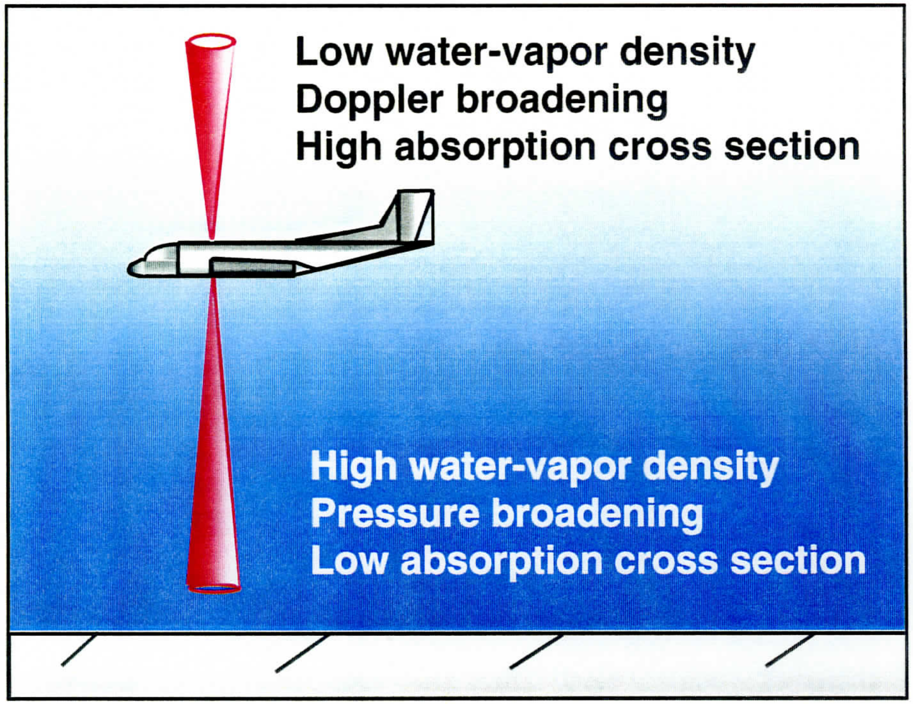
Part of the transmitted light-pulse is continuously backscattered as the pulse propagates through the atmosphere. This signal is collected by a receiver system for subsequent analysis.

DIAL = Differential Absorption Lidar



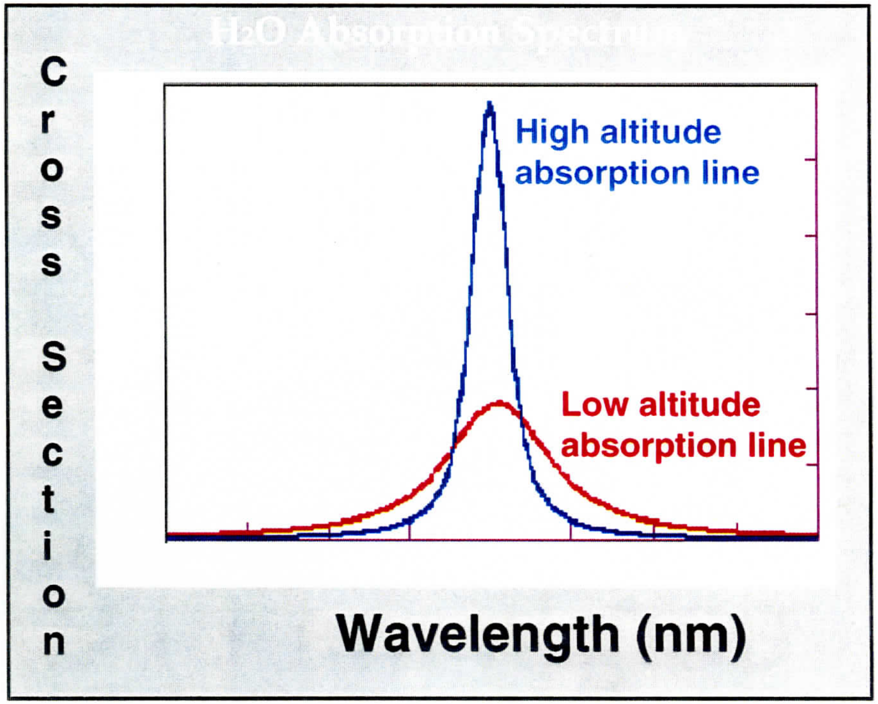
From the range-resolved **ratio** of off-line and on-line signal-**slope**, we can retrieve the absorbing-medium **density**-distribution versus altitude.

Advantages of the 940-nm region



Low water-vapor density
Doppler broadening
High absorption cross section

High water-vapor density
Pressure broadening
Low absorption cross section



Key features

H_2O lines in the 940-nm region are 20-times stronger than at lower-wavelength bands. Using these strong absorption lines, lidar measurements can be accurately extended to the upper troposphere / lower stratosphere.

940-nm OPA Research Objective

Develop and demonstrate a new solid-state laser transmitter that:

- can access suited H_2O absorption lines in the 930- to 960-nm spectral region,
- has enough output power to be usable in an airborne lidar system (i.e. > 1 W),
- has a narrow spectral-output compared to the H_2O absorption linewidth (spectral purity > 99%).

Approach

Use a non-linear crystal device to amplify the cw-output of a 940-nm diode laser.

Method: the 940-nm signal will be parametrically amplified in the crystal pumped by a doubled-Nd:YAG laser.

Challenge: A very high single-pass parametric gain has to be achieved for the signal beam.

Challenge

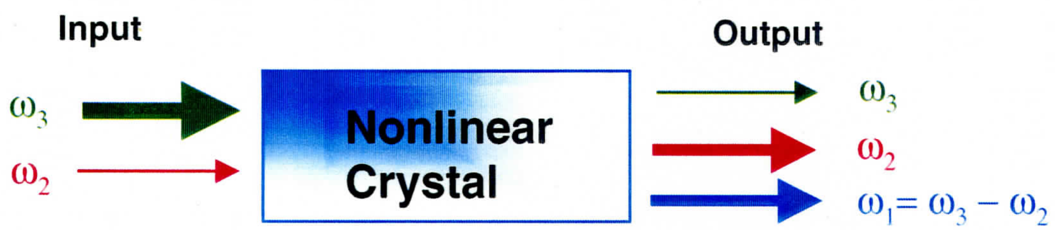
Take a 3- to 6-ns temporal-slice of a mW-level cw-beam and amplify it to mJ levels!

A 5-ns slice of a 5-mW beam at 940 nm contains 10^8 photons.
A 25-mJ pulse at 940 nm contains 10^{17} photons.

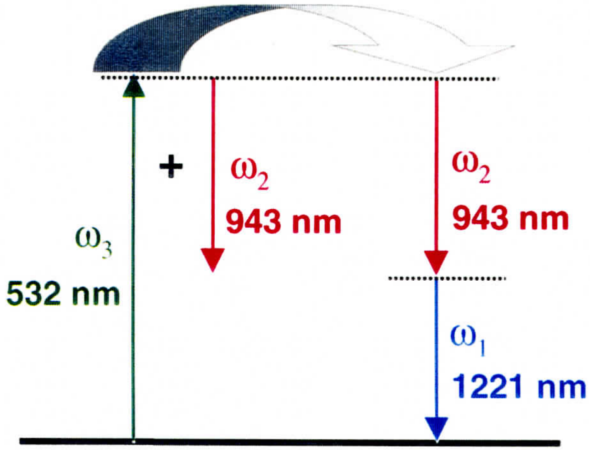
We need to design a non-linear device that will produce an **average gain approaching 10^9** for the 940-nm cw beam.

Optical Parametric Amplification

940-nm OPA



Geometry of the interaction



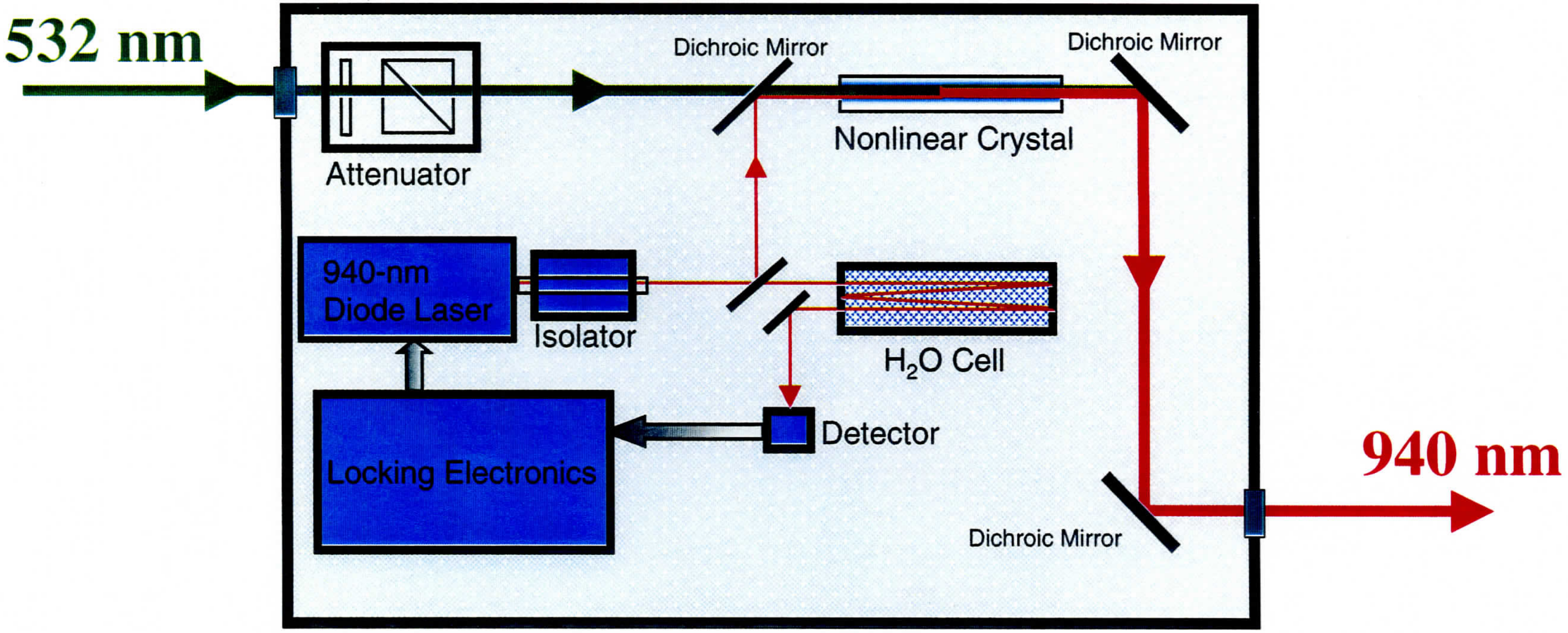
Energy Level Diagram

- The signal wave is amplified by the nonlinear mixing process.
- An idler wave is generated by the process.

Energy Conservation: $\omega_3 = \omega_2 + \omega_1$

Momentum Conservation: $\mathbf{k}_2 + \mathbf{k}_1 - \mathbf{k}_3 = \mathbf{0}$ $(\Delta k=0)$

940-nm Transmission Module



Pros & Cons of OPA Approach

The single-pass gain must be high if the pump pulse duration is limited to several nanoseconds, since OPAs, unlike lasers, don't have gain-storage time. But if the pump duration is made too short to increase gain, the transform-limited signal will be spectrally too broad.

Difference-frequency mixing (parametric generation) is not parametrically stable (even with $\Delta k=0$) because as soon as one of the waves (p, s, i) is depleted, its phase changes by π and the process backconverts. But backconversion can be inhibited between OPA stages.

Compared to a nanosecond-OPO, where phase changes across the beam resulting from uncontrolled multiple-backconversion broadens the spectral output, OPA has better spectral purity potential (i.e. transform limited).

At optical frequencies, spontaneous parametric emission (vacuum noise, i.e. +/- $h\nu$ per mode per volume) is significant (nW), but injection seeding of the signal at mW levels should control the parametric generation.

Equations for Modeling

The coupled equations describing the nonlinear mixing interaction, that need to be solved for every spatial grid-point (x,y,z) of every time-slice describing a Gaussian pulse, are:

$$\frac{d\mathcal{E}_s(x, y, z, t)}{dz} = i\,\frac{d_{eff}}{c}\,\frac{\omega_s}{n_s}\,\mathcal{E}_p\mathcal{E}_i^* \exp(i\,\Delta k\ z) - \alpha_s\mathcal{E}_s$$

$$\frac{d\mathcal{E}_i(x, y, z, t)}{dz} = i\,\frac{d_{eff}}{c}\,\frac{\omega_i}{n_i}\,\mathcal{E}_p\mathcal{E}_i^* \exp(i\,\Delta k\ z) - \alpha_i\mathcal{E}_i$$

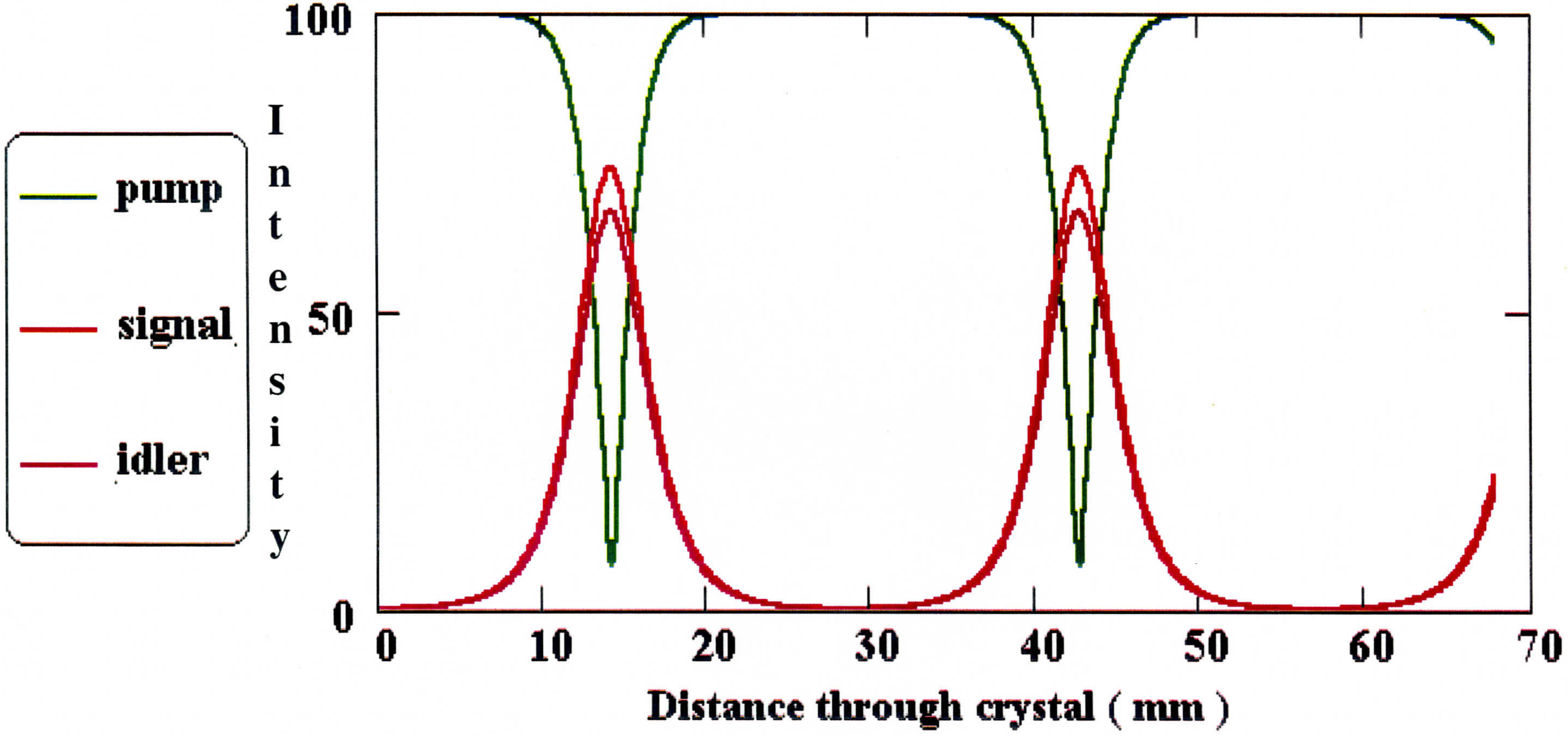
$$\frac{d\mathcal{E}_p(x, y, z, t)}{dz} = i\,\frac{d_{eff}}{c}\,\frac{\omega_p}{n_p}\,\mathcal{E}_s\mathcal{E}_i \exp(i\,\Delta k\ z) - \alpha_p\mathcal{E}_p$$

where the electric field E_ω at frequency ω is given by:

$$E_\omega(x, y, z, t) = \tfrac{1}{2}\left\{\mathcal{E}_\omega(x, y, z, t)\exp[-i(\omega t - kz)] + \mathcal{E}_\omega^*(x, y, z, t)\exp[i(\omega t - kz)]\right\}$$

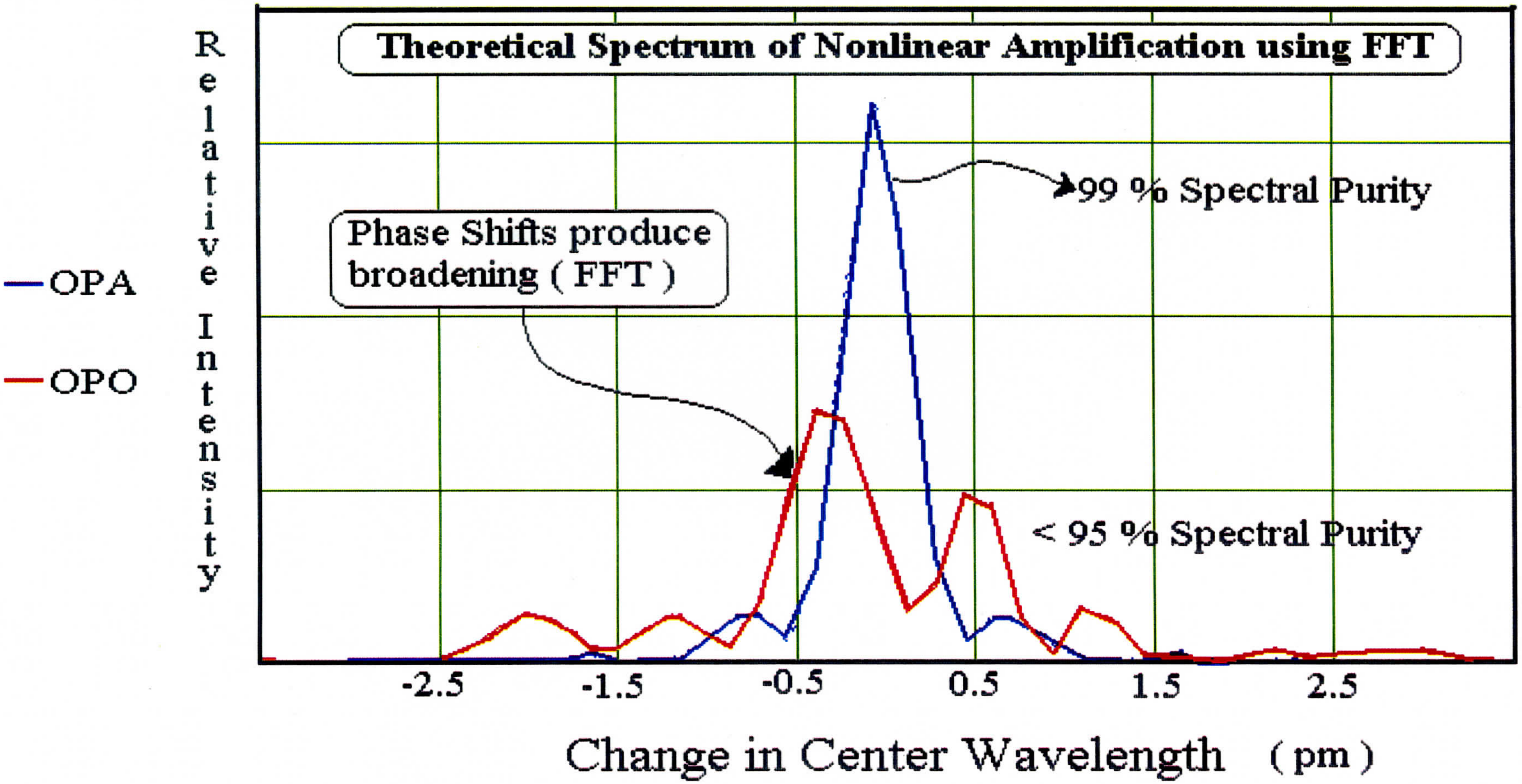
Conversion at Fixed Irradiance

940-nm OPA



OPO vs OPA Spectral Output

940-nm OPA



Theoretical Spectrum of Nonlinear Amplification using FFT

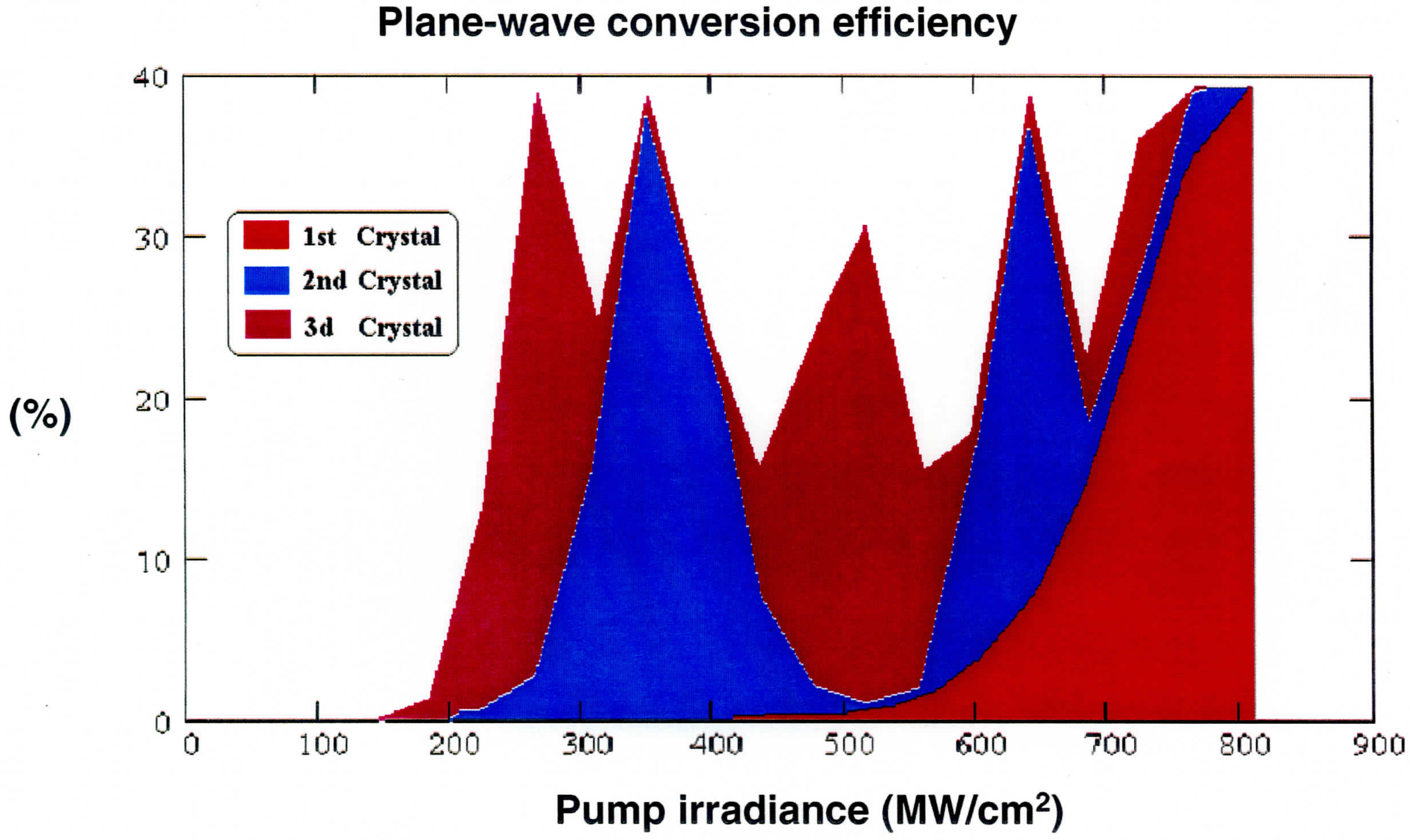
Phase Shifts produce broadening (FFT)

99 % Spectral Purity

< 95 % Spectral Purity

Three-Crystals OPA Simulation

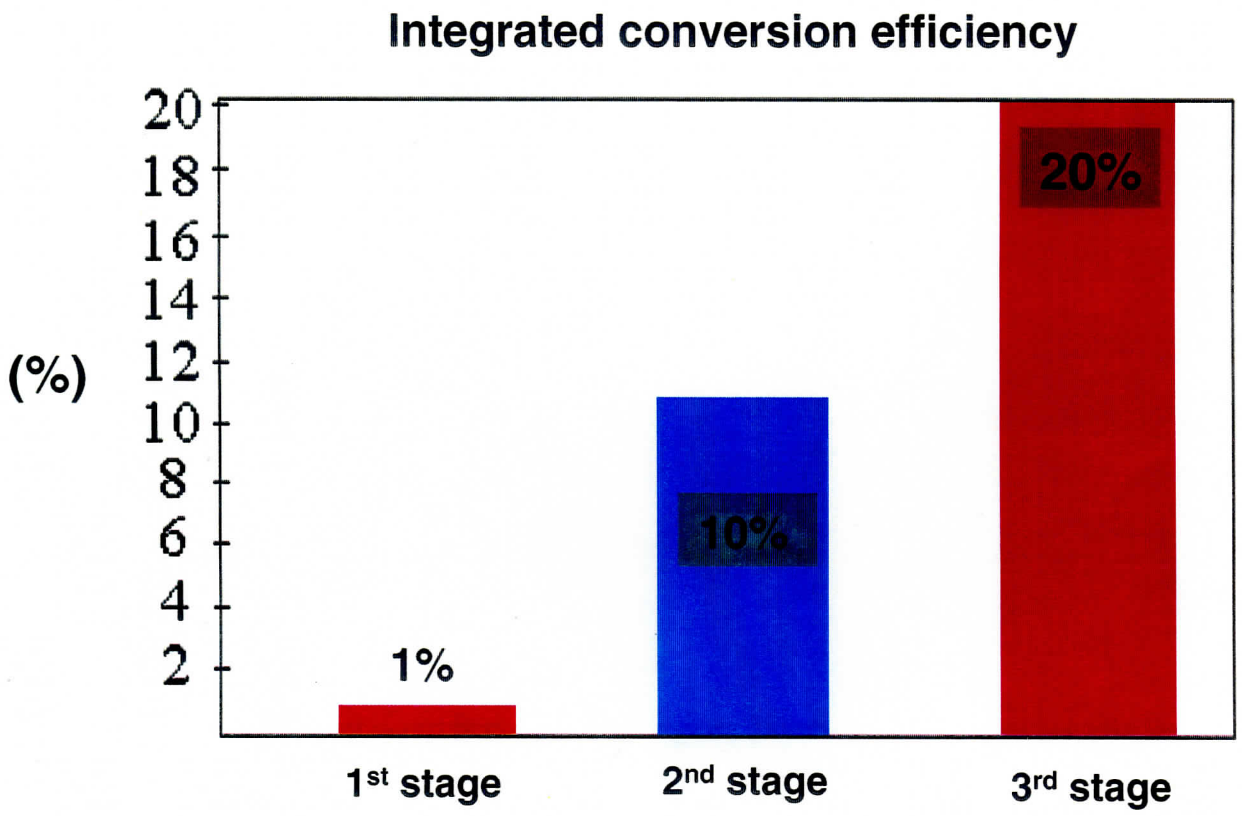
940-nm OPA


Plane-wave conversion efficiency

Configuration: 127-mm KD*P crystal followed by a 60-mm KD*P crystal and a 30-mm KD*P crystal

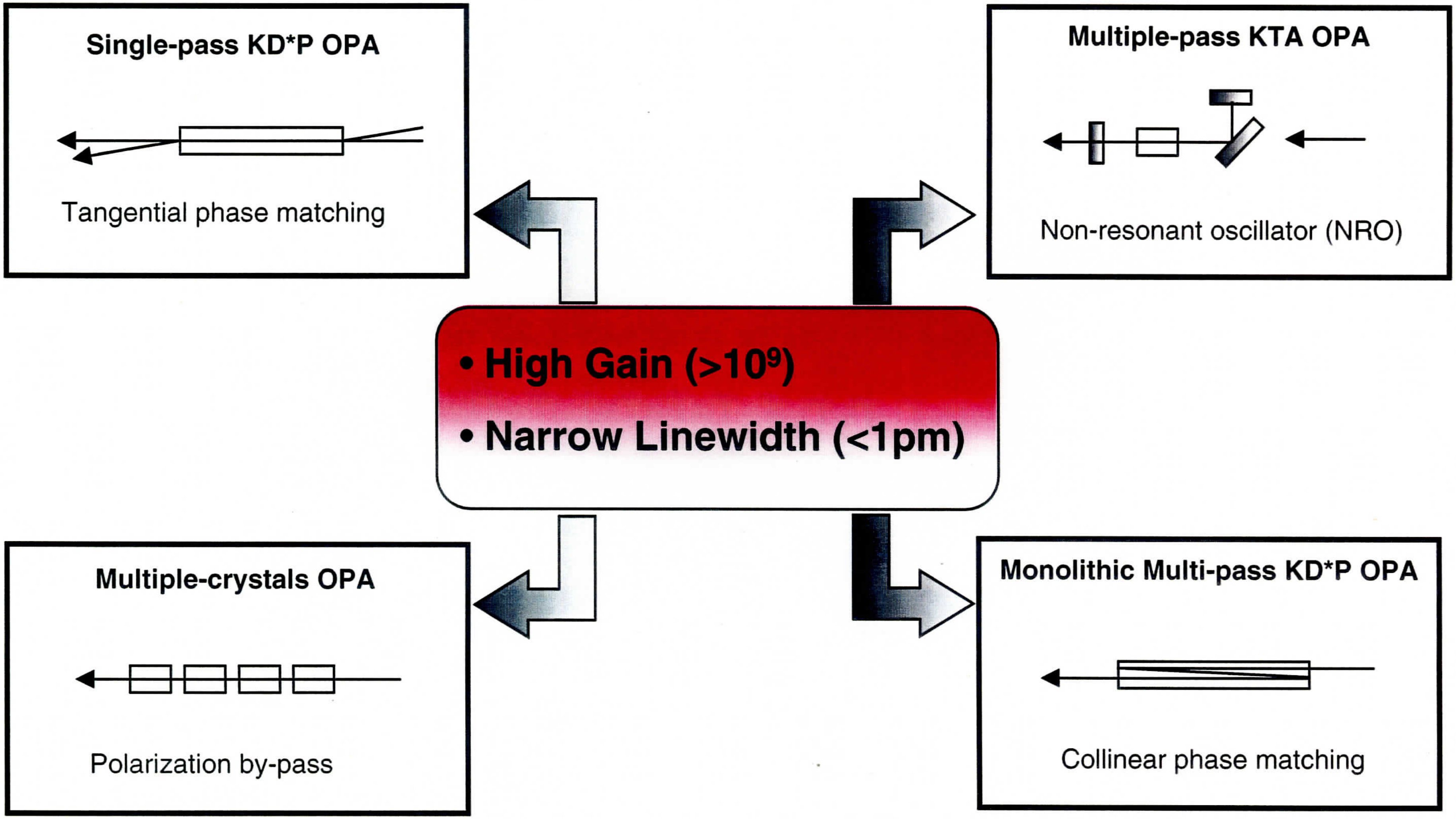
Three-Crystals OPA Simulation

940-nm OPA



<u>Configuration</u>: 127-mm KD*P crystal followed by a 60-mm KD*P crystal and a 30-mm KD*P crystal

Candidate OPA Configurations



- **High Gain ($>10^9$)**
- **Narrow Linewidth (<1pm)**

Single-pass KD*P OPA

Tangential phase matching

Multiple-pass KTA OPA

Non-resonant oscillator (NRO)

Multiple-crystals OPA

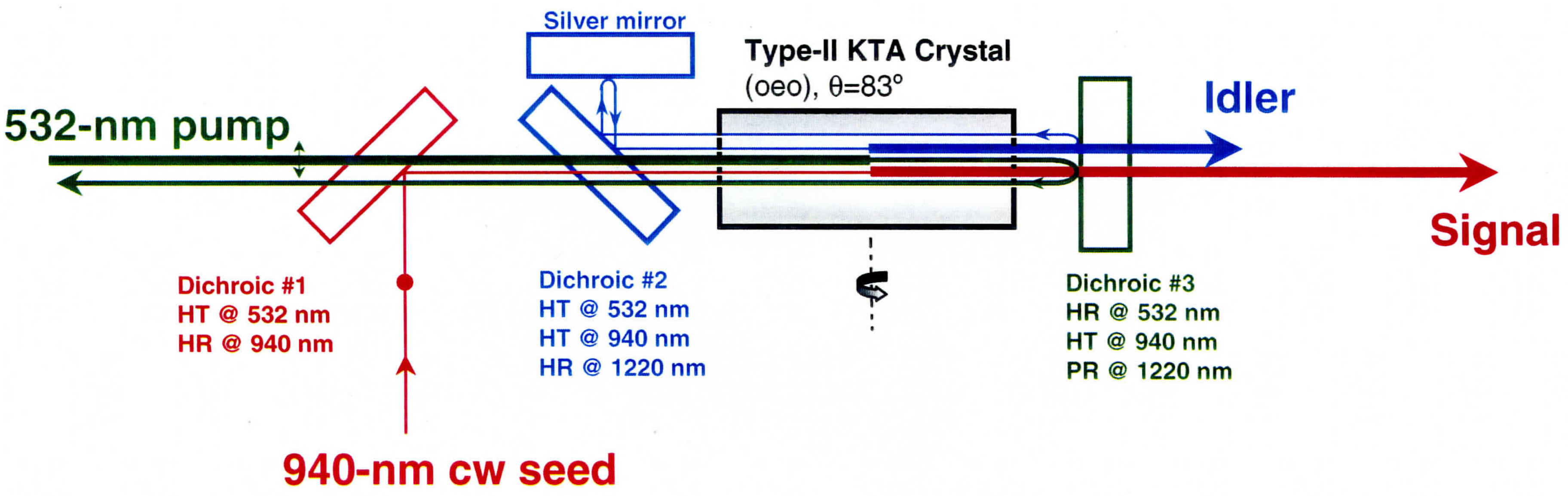
Polarization by-pass

Monolithic Multi-pass KD*P OPA

Collinear phase matching

Multi-pass OPA Setup (NRO)

940-nm OPA



L-shaped cavity that provides only partial feedback to the idler wave.
All other waves cannot resonate.

Multi-pass OPA Results (NRO)

940-nm OPA

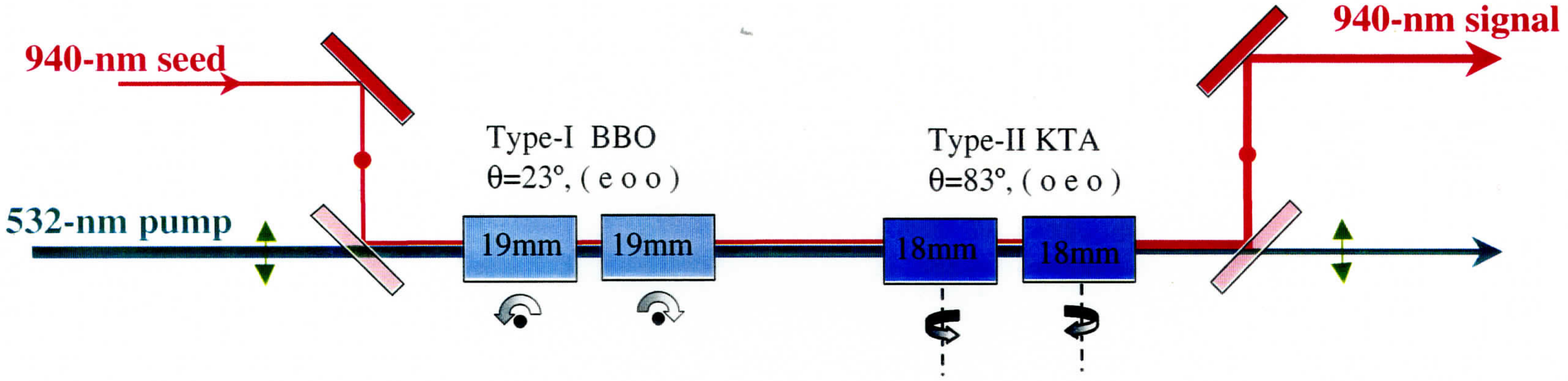
Pump energy is 190 mJ, and KTA crystal is 20-mm long

	Measured Conversion Efficiency	Corrected Conversion Efficiency	Measured Energy	Corrected Energy	Divergence
Signal	38%	41%	71 mJ	77 mJ	1 mrad
Idler	28%	30%	54 mJ	59 mJ	
Total	66%	71%	125 mJ	136 mJ	

Could not be controlled by input signal of seed source. Amplification was provided to spontaneous parametric generation.

Multiple-crystals OPA Setup

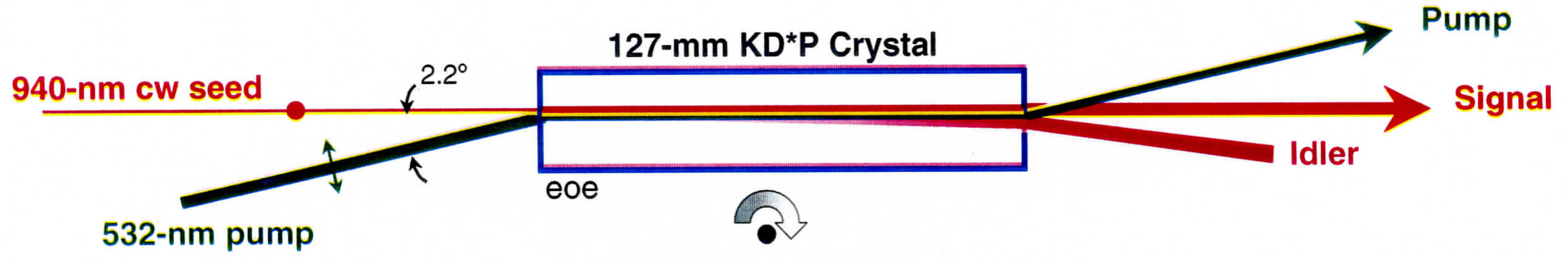
940-nm OPA



<u>Polarization by-pass configuration</u>: each stage has a different type of nonlinear interaction, making the idler-wave generated in the first stage ineffective in the second stage since it will have the wrong polarization.

Walk-off compensation in each segment of a stage increases acceptance bandwidth of the stage.

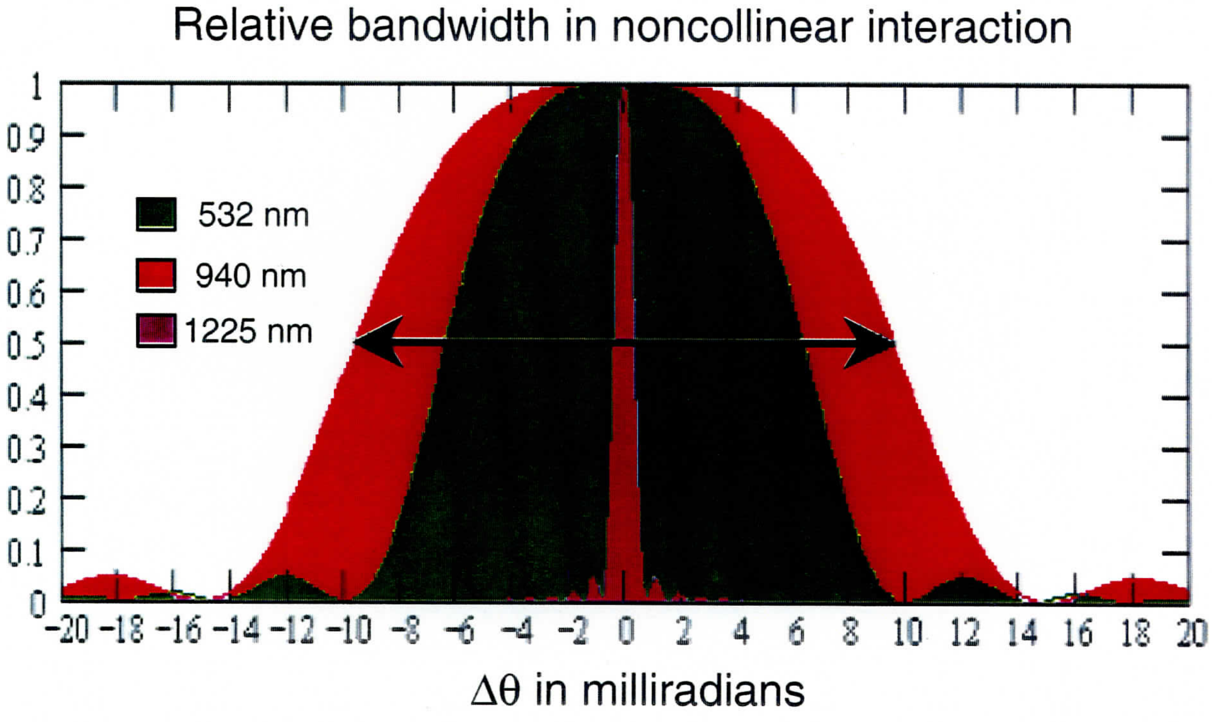
KD*P OPA Setup (1 pass)



Tangential phase matching configuration: impinging on the crystal, the pump and the signal seed are non-collinear, but the pump is an extraordinary beam and its Poynting vector walks-off in the birefringent crystal to co-align itself with the signal beam.

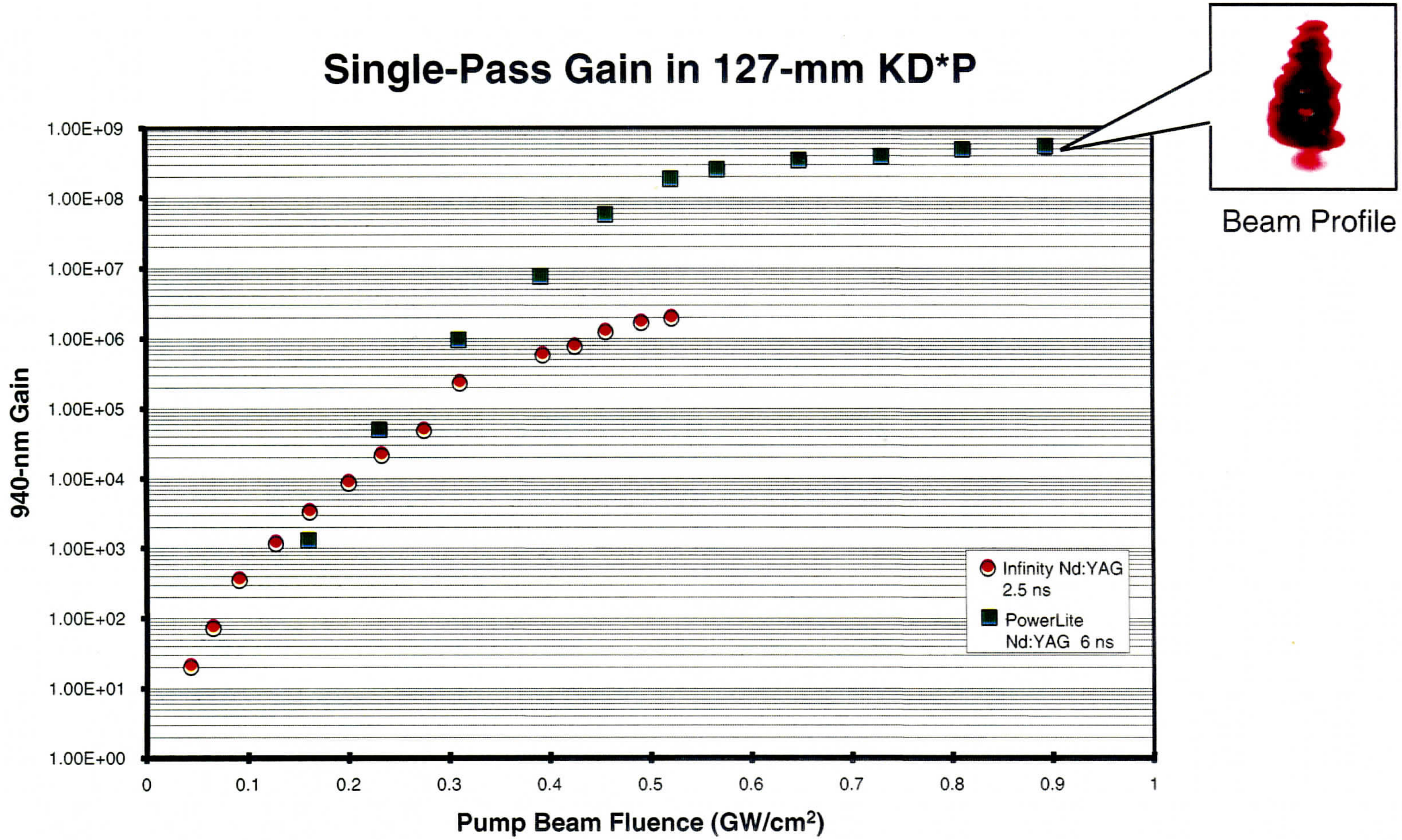
KD*P Angular Bandwidths

940-nm OPA



KD*P Experimental Results (1pass)

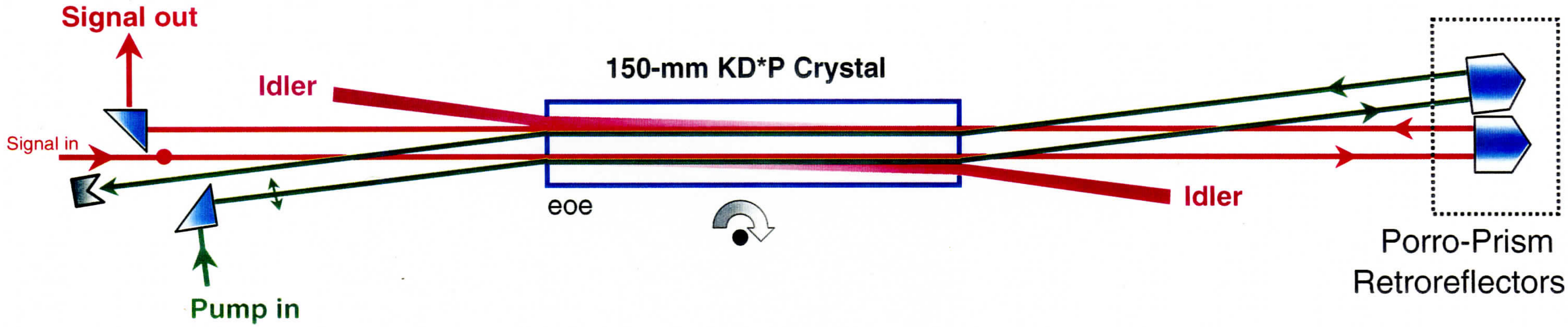
940-nm OPA



Single-Pass Gain in 127-mm KD*P

KD*P Double-Pass Configuration

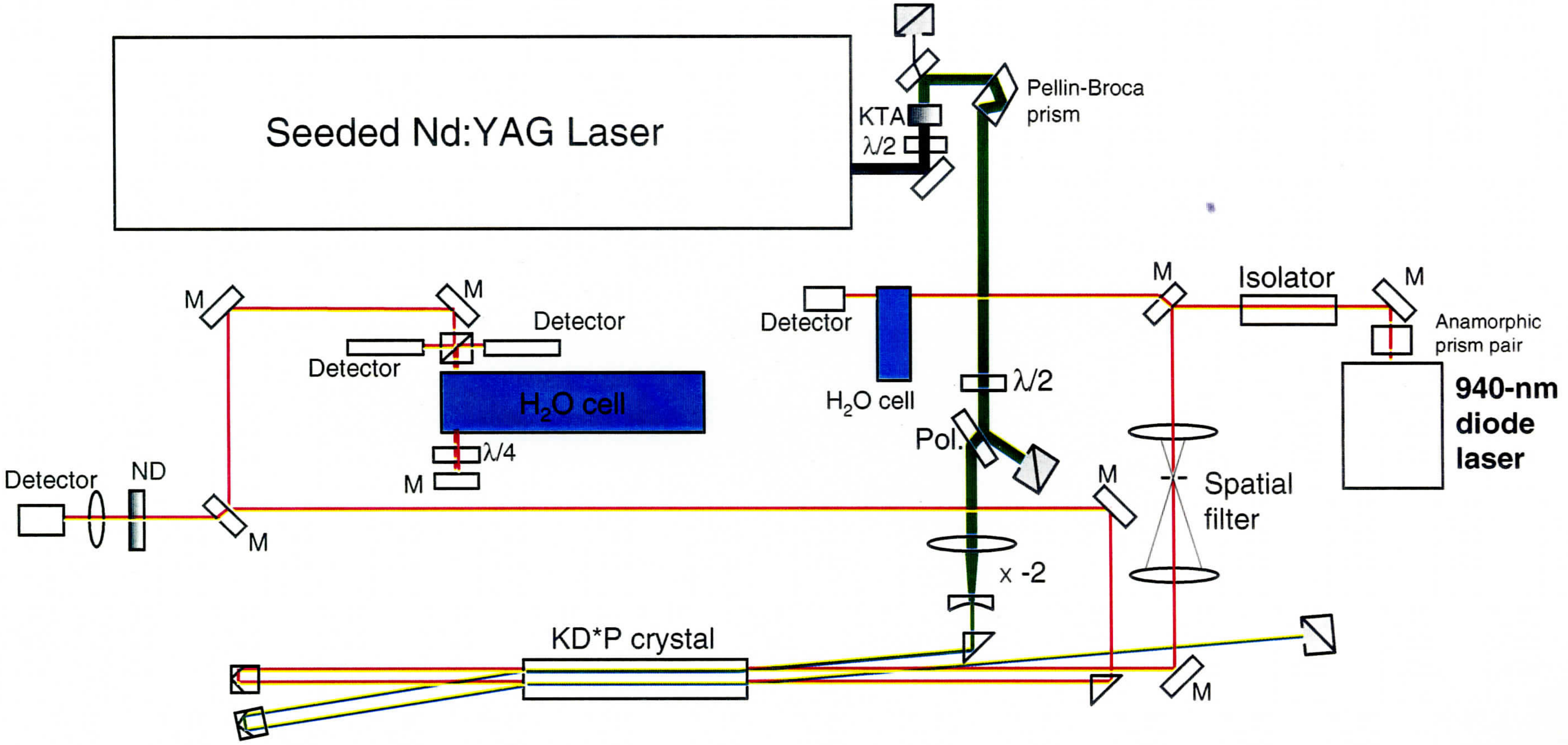
940-nm OPA



On the second pass, beams are larger due to the divergence resulting from down-collimation of the pump and signal beams. This effectively reduces the gain of the second stage and helps control the backconversion.

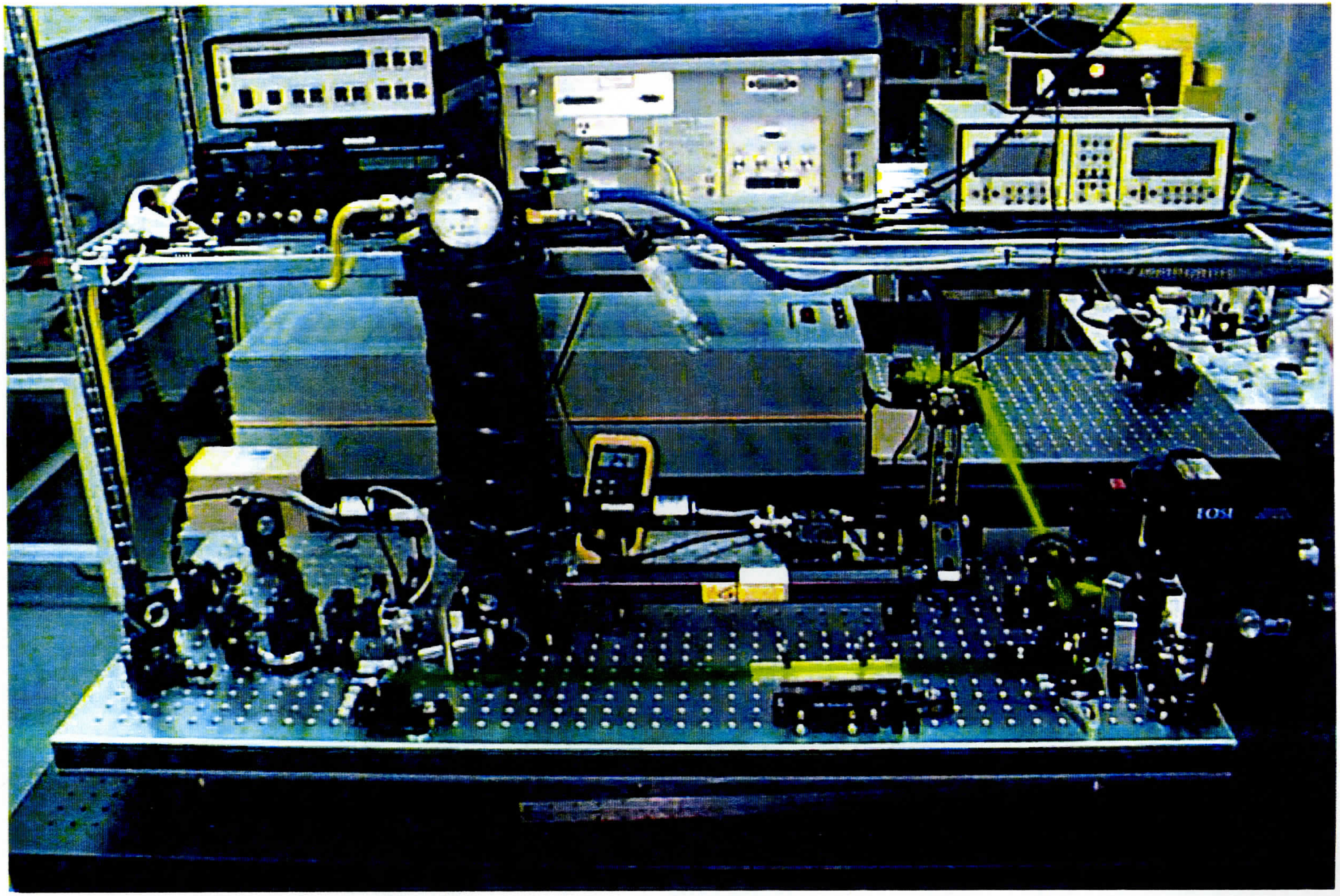
KD*P-OPA Experimental Layout

940-nm OPA



KD*P-OPA Experimental Layout

940-nm OPA



System Issues

- Parametric amplification with high gain can lead to parasitic oscillations which are deleterious for good spectral purity

- Back-conversion to the pump wavelength can and does occur. Optimizing the pump fluence and crystal length is necessary.

- A seeded Nd:YAG laser with good beam quality is necessary.

- Adequate isolation of diode from OPA is necessary at pump, signal and idler wavelengths. 940-nm diode lasers are not easy to procure.

- Careful selection of crystals with high damage-threshold, large transparency range, temperature insensitivity, and high angular and spectral bandwidth, needs to be done.

Status of Research (1)

- **KTA crystal were returned for correcting the cut and damage tested. OPA tests failed to obtained good parametric amplification of the seeded signal. KTA approach is abandoned unless satisfactory scheme to prevent parasitic oscillation is devised.**

- **Multi-pass monolithic KD*P OPA failed to produce expected parametric gain, probably due to insufficient facet reflectivity, the onset of Raman conversion, and the lower acceptance bandwidth of collinear phase matching. This approach is abandoned.**

- **The multi-pass OPA (NRO) was tested with both the KTA and the KD*P crystals. They both showed excellent conversion efficiencies but the KTA did not seed and the KD*P seeding was very unstable. We attributed this behavior to a resonance behavior of the NRO that oscillates due to the strong coupling of the three waves. This approach is also abandoned.**

Status of Research (2)

- The polarization by-pass technique remains a viable method if adequate crystal stages are identified. The PPRTA crystal is still in fabrication and is a good candidate for a first stage. This approach will be tried if crystal is delivered in time.

- A single-pass 127-mm KD*P crystal has parametrically amplified a 3-mw 940-nm seed-laser to 5 mJ/pulse. This represents a 1% conversion efficiency.

- The new 150-mm KD*P crystal with large clear aperture was tested in tangential phase-matching and showed excellent parametric amplification despite some residual spontaneous parametric amplification. We were able to configure the crystal in a double-pass scheme but gain was not measured due to a failure of the signal seeder. Double-pass configuration of the KD*P in tangential phase matching is our selected configuration, and spectral purity measurements will be conducted on this device.

- The model is in a final form and shows excellent prediction capabilities. Multi-stage devices can now be directly analyzed. Double-pass configuration of the KD*P is expected to boost efficiency to > 20%.