Development of a High Intensity Yb:YAG Pumped Optical Parametric Chirped Pulse Amplification Laser System

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Abstract

High intensity laser systems are finding many new applications in MeV to GeV particle generation and acceleration to Fast Ignition pulses for Laser Fusion Energy Drivers. In some cases, in order to enhance the electric fields associated with the laser plasma interactions longer wavelengths are advantageous. Thus, there is considerable interest in the development of high intensity systems in the infrared part of the spectrum. In the current study we are developing a TW class optical parametric chirped pulse amplifier (OPCPA) system. The pump laser for this system will consist of a femtosecond Yb:glass oscillator which will be stretched to the order of 100 ps and amplified in a diode pumped Yb:YAG ceramic slab amplifier system up to an energy of around 2 J. A seed pulse for the OPCPA system at a wavelength of around 1500 nm will be created from white light continuum generated from the femtosecond pulse after amplification to the microjoule level. This seed pulse will be stretched and amplified in several stages of optical parametric amplification to a final energy of the order of 400 mJ. The final pulse will then be recompressed to a pulse duration of the order of 100 fs to give a 4 TW output pulse. The proposed system design and initial development tests will be presented and discussed.

Optical Parametric Chirped Pulse Amplification OPCPA

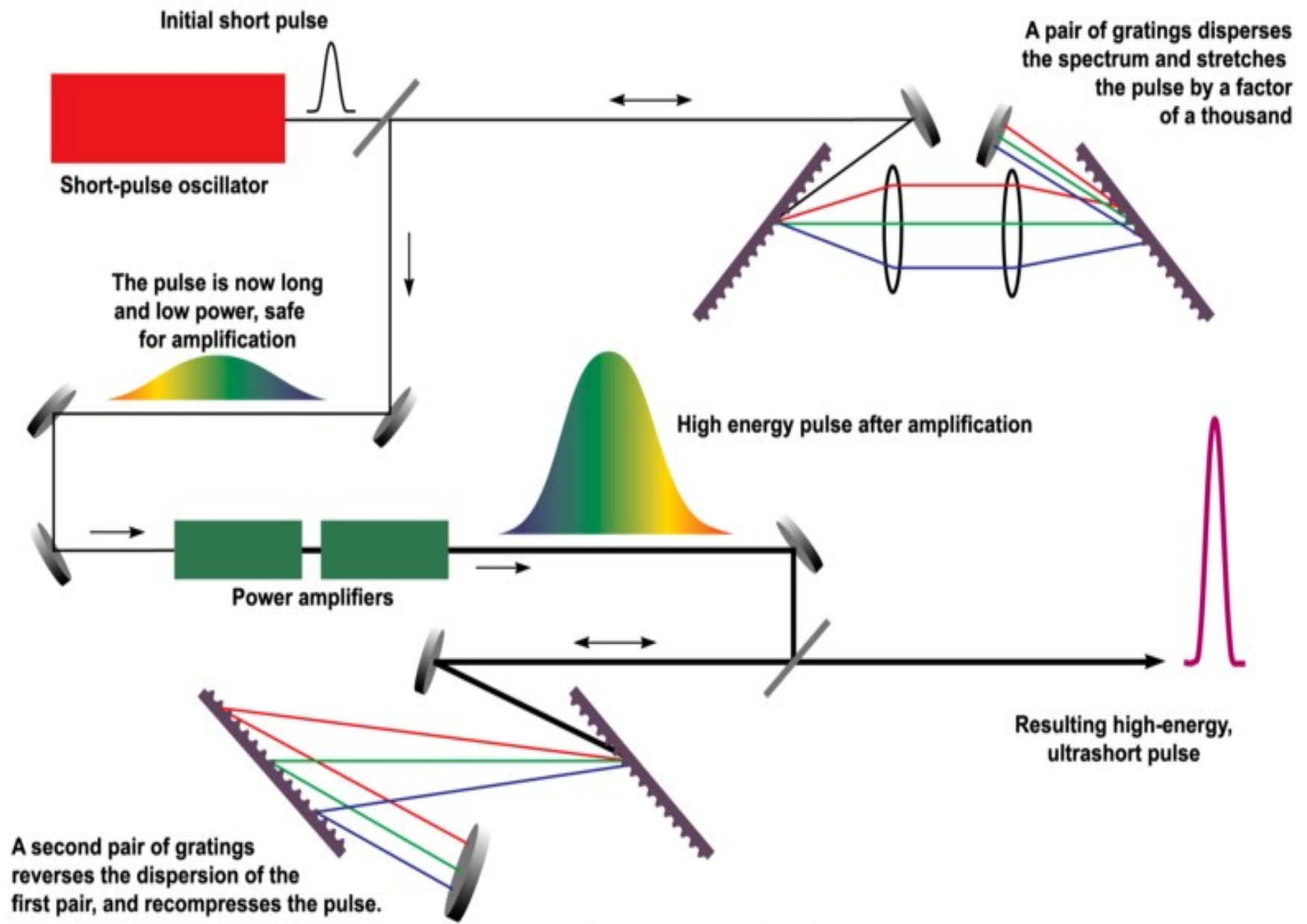

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Fig (1) Block Diagram of the OPCPA System

OPG and OPA Background

- Optical parametric generation (OPG) is employed to generate tuneable coherent optical pulses for optical parametric amplification (OPA). The input is one light beam of frequency ω_p, and the output is two light beams of lower frequencies ω_1 and ω_2, with the requirement $\omega_p=\omega_s+\omega_i$. These two lower-frequency beams are called the "signal" and "idler".
- A nonlinear optical crystal is used to split the photon of an incident laser pulse (pump) into two these lower-energy photons.
- The wavelengths of the signal and the idler are determined by the phase matching condition, controlled by some factors, e. g. by temperature or, in bulk optics, by the angle between the incident pump laser ray and the optical axes of the crystal.
- The output beams from OPG are typically comparatively weak and are somewhat spread-out in direction and frequency. This complication is solved by using further optical parametric amplification (OPA). The OPA will amplify the ω_s beam, and also create a new beam at the frequency ω_i with $\omega_p=\omega_s+\omega_i$ because of the conservation of photon energy.
- Phase matching can typically be achieved by angle tuning of the crystal, dispersion will limit the spectral bandwidth over which phase matching is accomplished.
- Group Velocity Matching GVM condition is fulfilled when the group velocities of both signal and idler pulses are also made equal along the seed beam propagation direction.

OPCPA Background

- OPCPA technique was first proposed by Dubietis et al. in 1992[1]. With a factor of ~2x10^4 without bandwidth limitation in a BBO crystal, chirped pulses have been parametrically amplified, then they were compressed down to 70 fs to achieve maximum power of ~90 GW.
- Noncollinear Parametric interaction in nonlinear optical crystals has been introduced in 1967 by Douglas Magde et al.[2] while noncollinear phase matched optical parametric generation is only recently attracting attention as an innovative technique for ultrashort pulse generation[3].
- High power OCPA systems already are being built with specific features and there are some challenges while designing and implementing OPCPA and they can be summarized as: ***pump-seed synchronization*** which can be accurately achieved by using a master oscillator power amplifier (MOPA), ***temporal pulse contrast*** which can be addressed by controlling the seed pulse intensity and gain per amplification pass, controlling ***wavelength dependent saturation effects***, ***seed-pump phase matching***, and ***carrier envelope phase control (CEP) where required.***

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OPCPA Systems

- A number of high power optics labs all over the world are building OPCPA systems. The competition is to shorten the pulse while increasing the pulse peak power.
- One of these labs is Center for Free Electron Laser Science CFEL in Hamburg, Germany to generate optical waveform with 5.9 ps pulse duration with 8 GW peak power[4].
- Other labs like ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, and ICREA-Instituci´o Catalana de Recerca i Estudis Avanc¸ats, Barcelona, Spain[5], Max-Planck-Institut für Quantenoptik, Garching, Germany, Department für Physik, Universität München, Germany[6], Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller University Jena, Germany[7]. All of these labs are working on developing the OPCPA systems with peak powers in the range of 13 MW to 16 TW and pulse lengths in the range of 4 fs to 96 fs.
- We are developing an OPCPA system having its seed generated and extracted from white light generation (continuum) phenomenon from a femtosecond Yb:fibre laser oscillator. The pump pulse is derived from the same seed pulse stretched to the picosecond scale and amplified. Thus both pump and seed are accurately synchronized and amplification will be carried out in non-colinear phase matching inside KTA crystals to obtain a high gain and large bandwidth. The amplified will be then compressed to the femtosecond scale on the order of 100 fs with pulse energy of 400 µJ to give a peak output power of 4 TW.

Proposed System Block Diagram

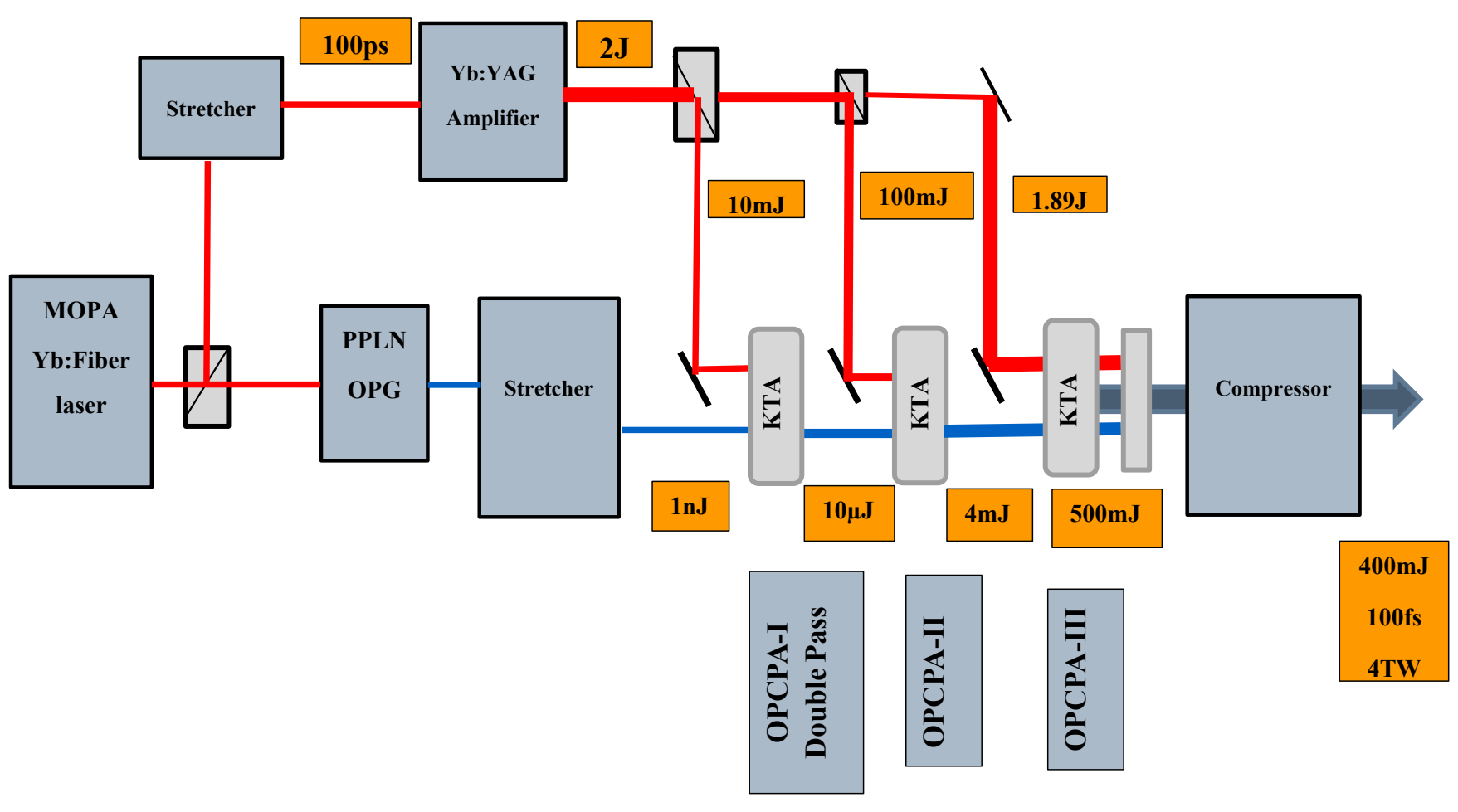


Fig (2) Block Diagram of the Proposed Terawatt OPCPA System

KTA Nonlinear Optical Crystal

- **Potassium Titanyl Arsenate ($KTiOAsO_4$ or KTA)** optical non-linear crystal developed recently has excellent non-linear optical and electro-optical coefficients which are higher in comparison with KTP crystal.
- The main advantages of KTA in comparison with KTP are slightly higher values of second-order nonlinear coefficients [8-11], a longer IR cutoff wavelength, and the absence of significant absorption at 3.5µm [12] and in the 2-5µm region[13].
- The large non-linear coefficients are combined with broad angular and temperature bandwidths. Additional advantages of the Arsenates are low dielectric constants, low loss tangent and ionic conductivities orders of magnitude less than KTP.
- OPO devices based on these crystals have been demonstrated as reliable, solid state sources of tunable laser radiation exhibiting energy conversion efficiencies above 50%. KTA has a very high damage threshold. No optical damage was observed at the levels of 10 - 20 GW/cm² with picosecond dye lasers. This crystal is grown using high temperature flux technique.
- The biaxial crystal KTP and its analogs including KTA have broadband type II phase matching near 1.56µm[15], however the gain in these crystals is lower than what is normally available for visible pump wavelengths. Further developments of quasi-phasematched periodically poled nonlinear media has improved the gain and interaction lengths at mid-IR wavelengths[14,17].

Phase Matching and K-Vector Analysis

Mixing optical waves through Optical Parametric Oscillation OPO process is beneficial only if the interacting waves have the same phase velocity in the nonlinear medium, i.e. the phase matching conditions must be satisfied. During this process conservation of energy and conservation of momentum are required as in equation (1). The phase matching angles for 1030 nm pump wavelength were calculated using equations (3) and (4) based on Sellmeier equation for indices of refraction n_x, n_y and n_z as in equation (5) [16]. Finally the three noncolinear waves the pump, signal and idler should meet the condition in equation (2) for phase matching K-vector analysis.

$$\left.\begin{matrix}\hbar & \hbar & \hbar \\ \hbar & \hbar & \hbar\end{matrix}\right\}\text{..........(1)}$$

$$\Delta \vec{\kappa} - \vec{\kappa}_p - \vec{\kappa}_s - \vec{\kappa}_i - \upsilon\text{.......................(2)}$$

$$\sin\theta_{PM} = \frac{n_z(\lambda_b)}{\eta_y(\lambda_c)\cos\alpha - \eta_y(\lambda_a)\cos(\alpha+\beta)}\times\ldots$$

$$\ldots\left\{\frac{\eta_x^2(\lambda_b) - \left[\eta_y(\lambda_c)\cos\alpha - \eta_y(\lambda_a)\cos(\alpha+\beta)\right]^2}{n_x^2(\lambda_b) - n_z^2(\lambda_b)}\right\}^{1/2}\text{..(3)}$$

$$\beta = \arcsin\left[\frac{\eta_y(\lambda_c)}{\eta_y(\lambda_a)}\sin\alpha\right] - \alpha\text{............(4)}$$

α is the angle between pump and seed

$\eta = n(\lambda)/\lambda$

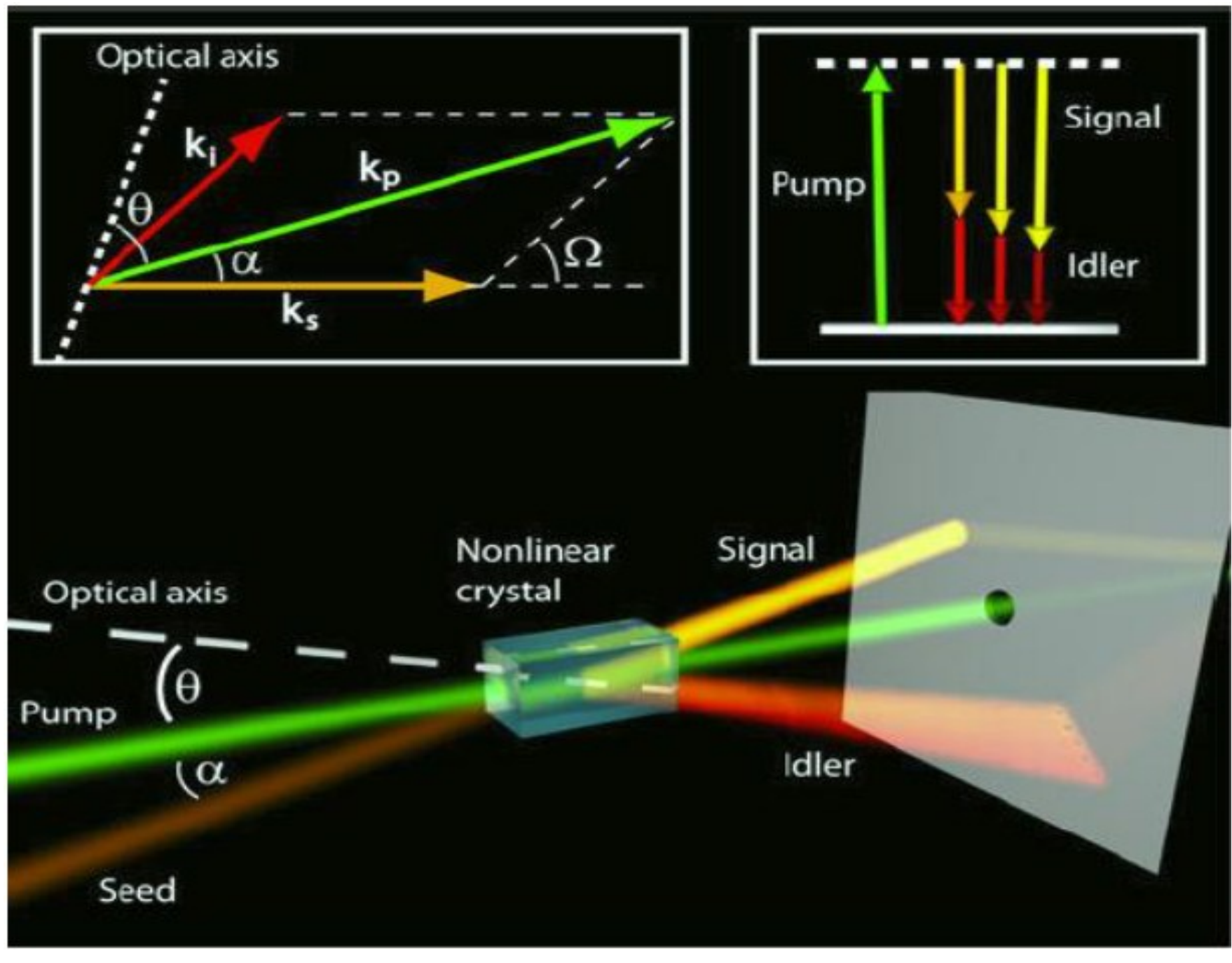


Fig (3) Phase Matching and K-Vectors in Nonlinear Optical Crystal [19]

KTA Crystal Sellmeier Equations

$$n_x(\lambda) = \left[1.90713 + \frac{1.23522}{1-\left(\frac{0.19692}{\lambda}\right)^2} - 0.01025\lambda^2\right]^{1/2},$$

$$n_y(\lambda) = \left[2.15912 + \frac{1.00099}{1-\left(\frac{0.21844}{\lambda}\right)^2} - 0.01096\lambda^2\right]^{1/2},\text{.....(5)}$$

$$n_z(\lambda) = \left[2.14786 + \frac{1.29559}{1-\left(\frac{0.22719}{\lambda}\right)^2} - 0.01436\lambda^2\right]^{1/2},$$

Phase Matching Curves

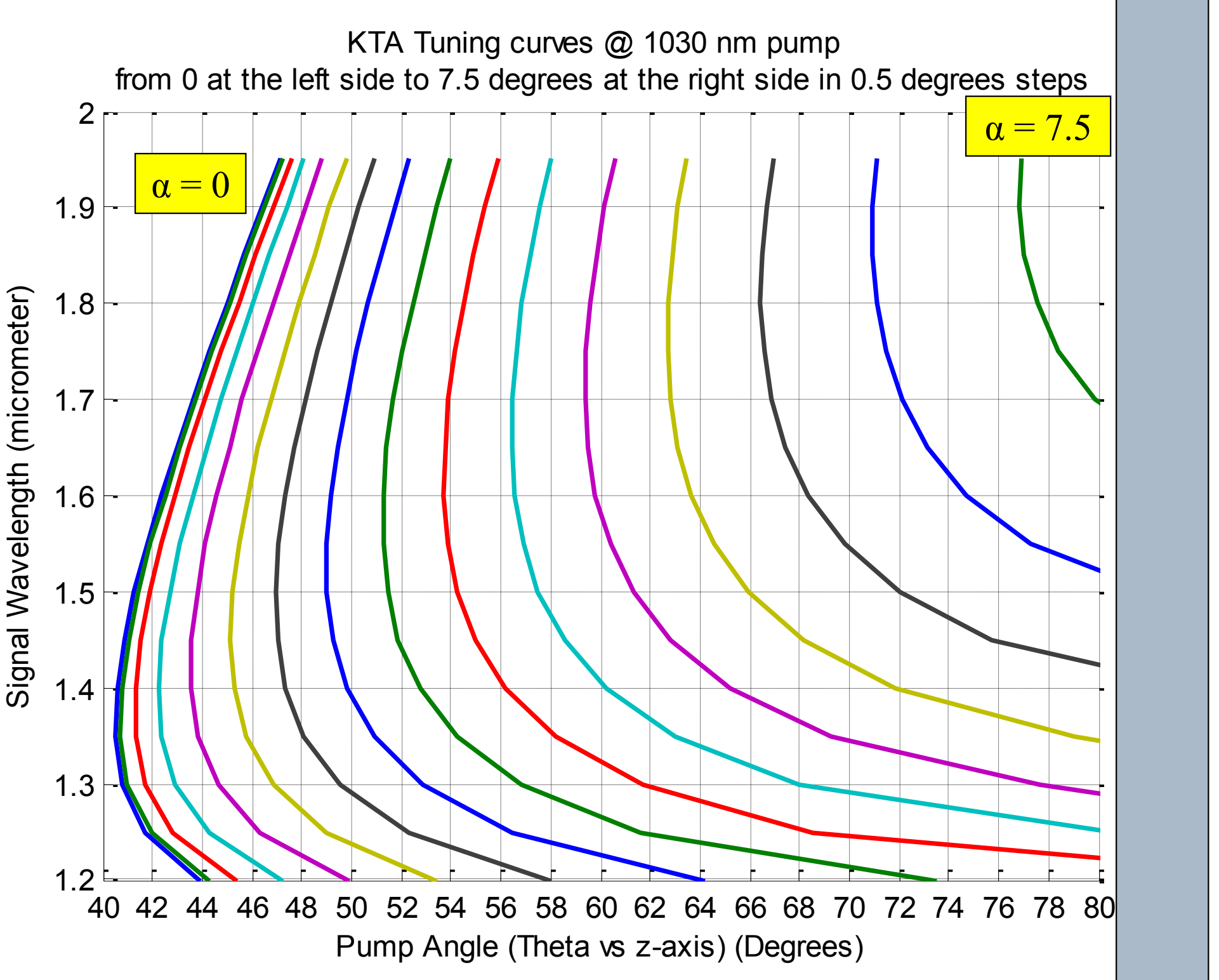
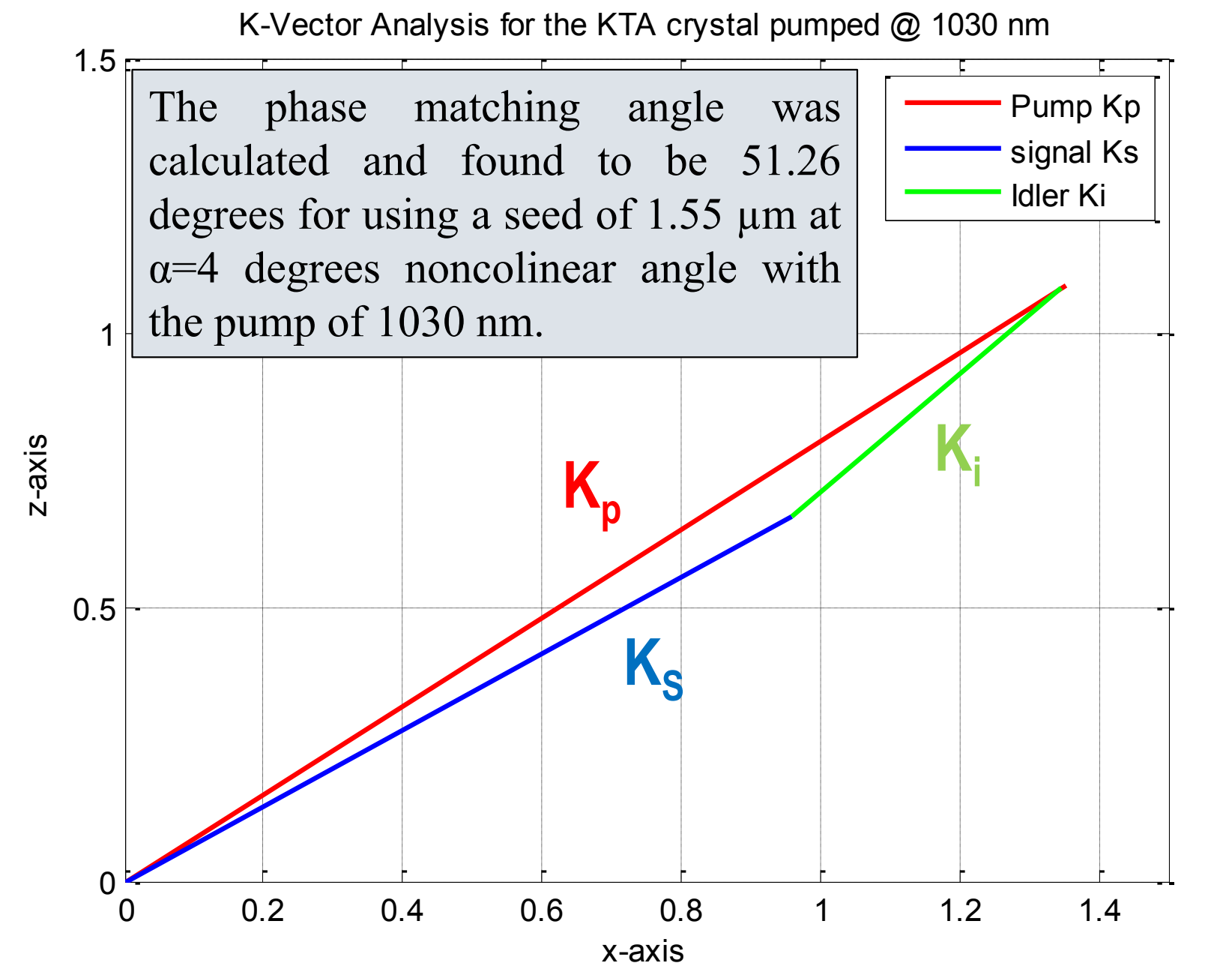


Fig (4)

K-vector analysis



The phase matching angle was calculated and found to be 51.26 degrees for using a seed of 1.55 µm at α=4 degrees noncolinear angle with the pump of 1030 nm.

Fig (5)

Seed Generation

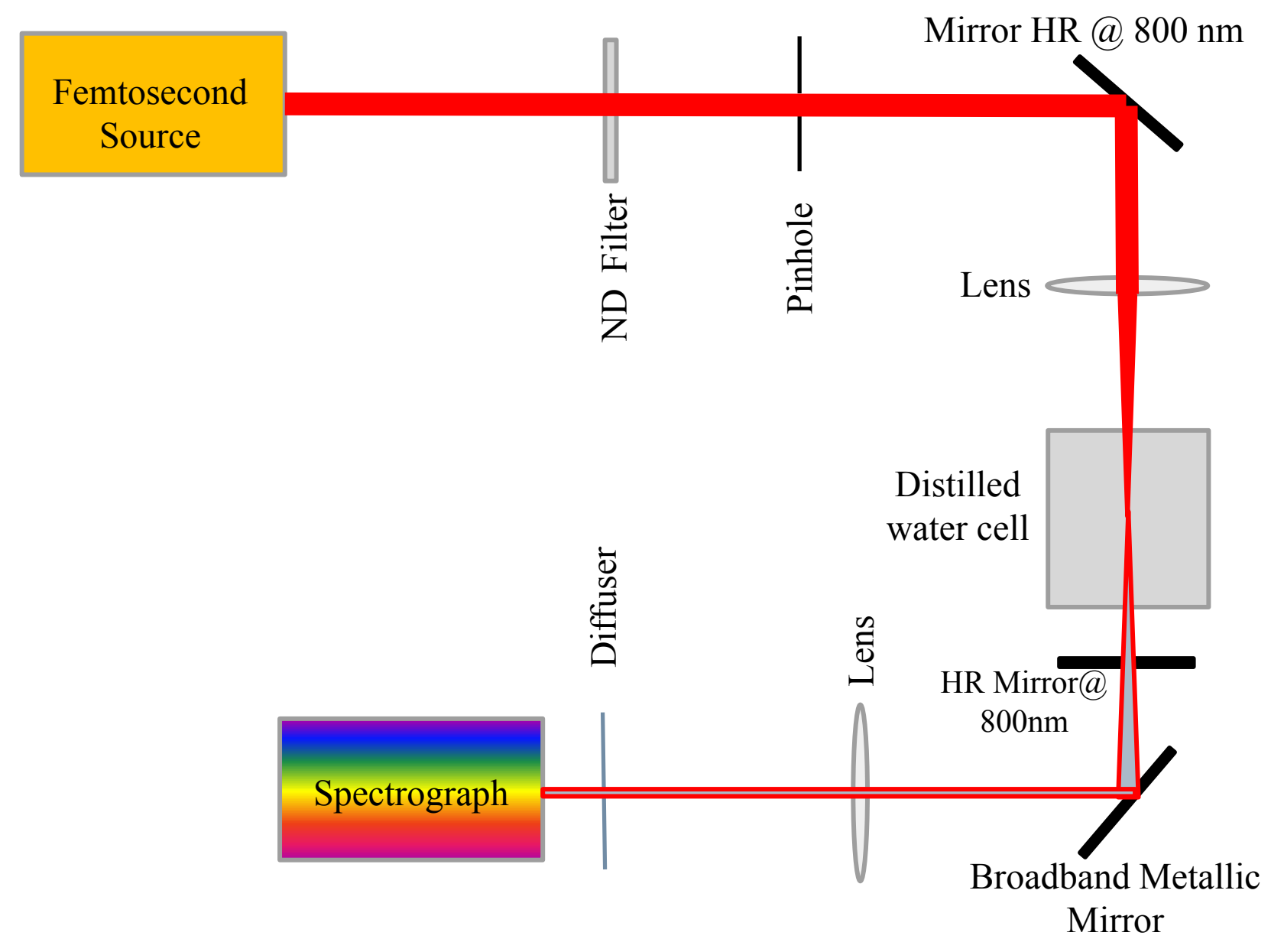


Fig (6) White Light Generation Setup

Conclusion

We are developing a TW OPCPA system. To guarantee that both seed and pump are synchronized, the same femtosecond Yb:fiber master oscillator is used to generate the white light continuum seed pulse and also the pulse which will be stretched to the picosecond scale and amplified then used as pump for the OPCPA stages. Thus both pump and seed are accurately synchronized and amplification will be carried out in non-colinear phase matched geometry inside KTA crystals that was calculated to obtain a high gain and large bandwidth. The best phase matching angle was found to be 51.26˚ at 1030 nm pump signal. The phase matching angle calculations were checked by using the K-vector analysis. The amplified pulse will be then compressed to the femtosecond scale on the order of 100 fs with pulse energy of 400 mJ to give a peak output power of 4 TW.

Acknowledgement

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