Generation of Ultra-fast CO_2 Laser Pulses using Self-Phase Modulation in a Gas-filled Hollow Waveguide

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High peak power CO_2 lasers

Potential applications

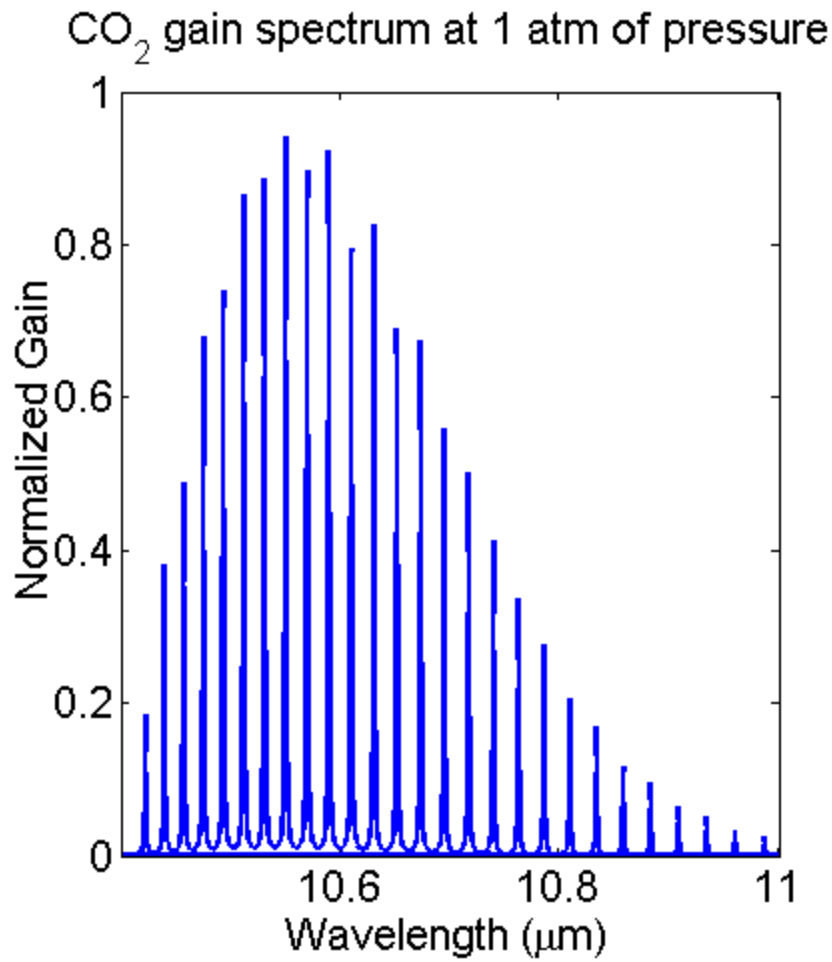
- ✓ Laser acceleration of ions
- ✓ Broad band radiation generation from 2 – 20 um
- ✓ Propagation of a laser over kilometers due to laser filamentation

Comparison to conventional high peak power laser systems

Nd:Glass/Ti:Saph	**CO_2**
1 um	10 um
100 TW - 1 PW	Limited progress
Chirped pulse amplification	No need for CPA

Challenge in high power CO_2 laser development

- Disadvantage of CO_2 lasers
  - Low natural bandwidth compared to solid state lasers
  - At 1 atm bandwidth can sustain nanosecond pulses
  - Ti:Saph and Nd:Glass can sustain femtosecond time durations



$$\Delta\nu = 3.5\ GHz/atm$$

D.J. Haberberger, S. Ya. Tochitsky, and C. Joshi. 15 terawatt picosecond CO_2 laser system. Opt. Express **18**(17), 17865-17875 (2010) .

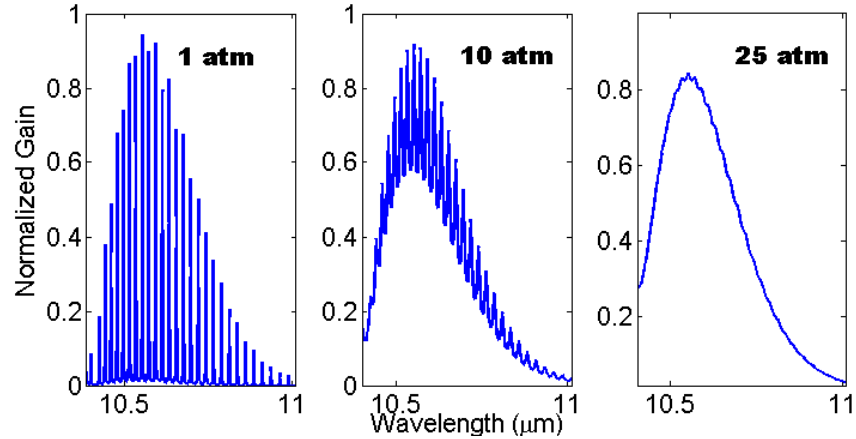
Amplification of picosecond pulses in a CO_2 laser – broadening mechanisms

- <u>Pressure Broadening</u>

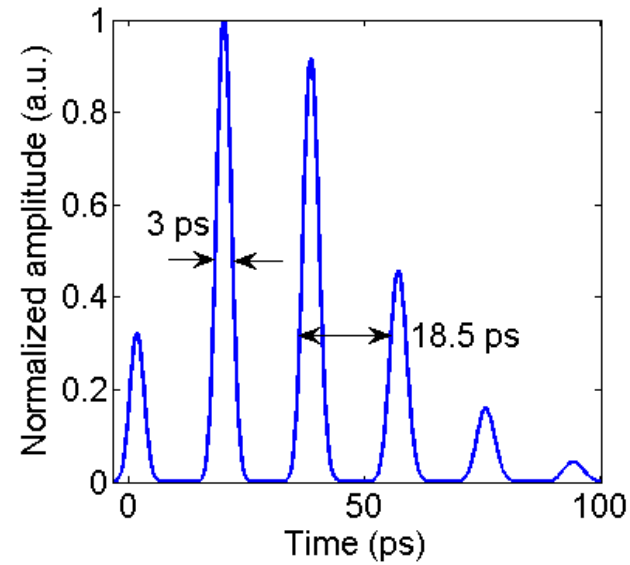
$$\frac{1}{\nu_{collision}} < \tau_{transition}$$

$$\Delta E \Delta \tau \geq \hbar/2$$

$$\nu_{pressure} = P(5.79\Psi_{CO_2} + 4.25\Psi_{N_2} + 3.55\Psi_{He})$$



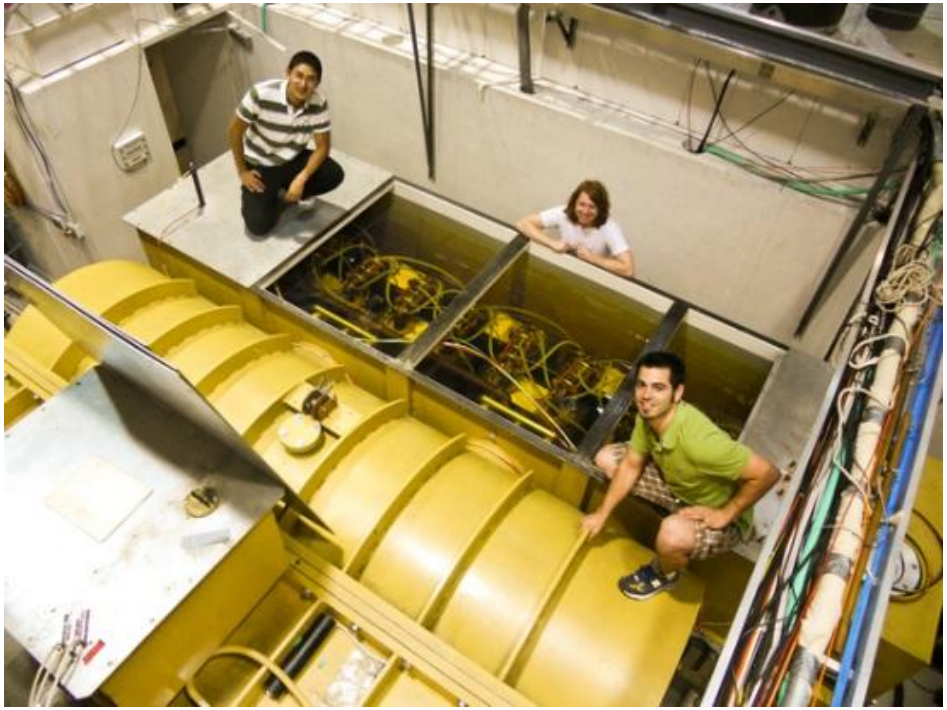
Pulse train formation
- Modulation is 1/55 GHz = 18ps



D.J. Haberberger, S. Ya. Tochitsky, and C. Joshi. 15 terawatt picosecond CO_2 laser system. Opt. Express **18**(17), 17865-17875 (2010) .

Neptune Laboratory's 15 TW CO_2 laser system

- 15 TW – 100 J in 3 ps
- Relies on multi-atmosphere final amplifier
- Can only be fired once every 5 minutes
- Applications would benefit from a higher repetition rate



D.J. Haberberger, S. Ya. Tochitsky, and C. Joshi. 15 terawatt picosecond CO_2 laser system. Opt. Express **18**(17), 17865-17875 (2010) .

Amplification of short pulses in a 1 atm CO_2 laser

- <u>Field Broadening</u>

Rabi frequency

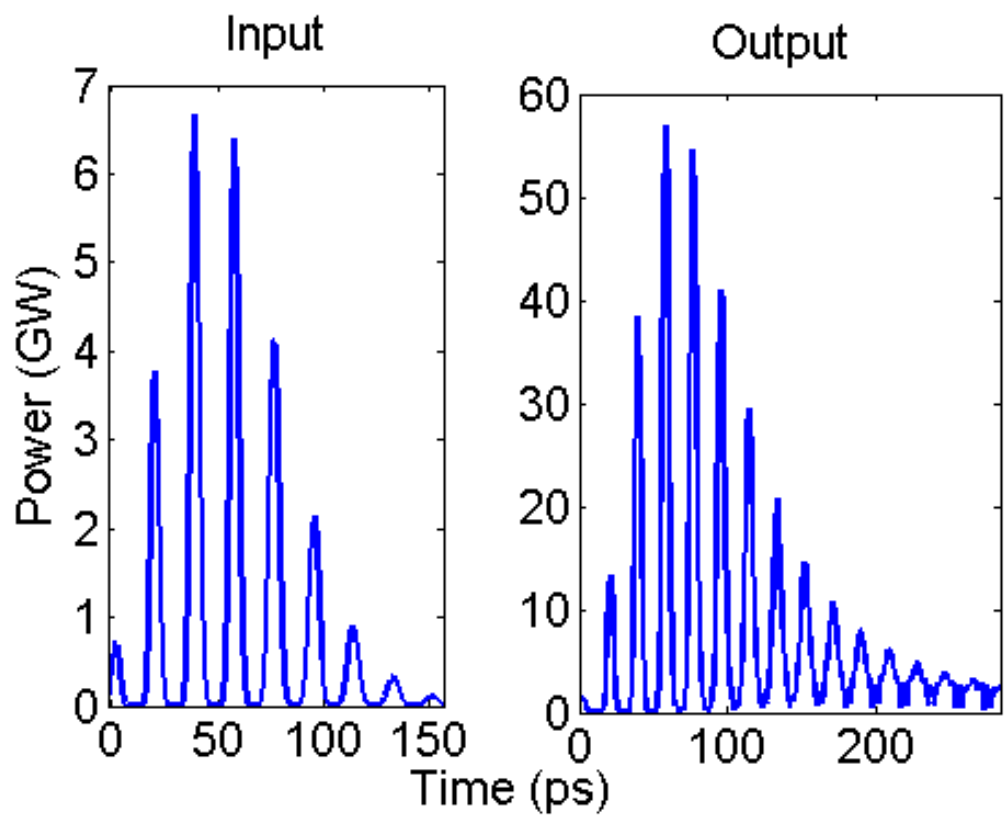
$$\Delta\nu \approx \Omega_R = 1.38 \cdot 10^7 \mu\sqrt{I})$$

Example:

$$I = 5\ GW/cm^2$$
$$\Delta\nu \approx 30.3\ GHz$$

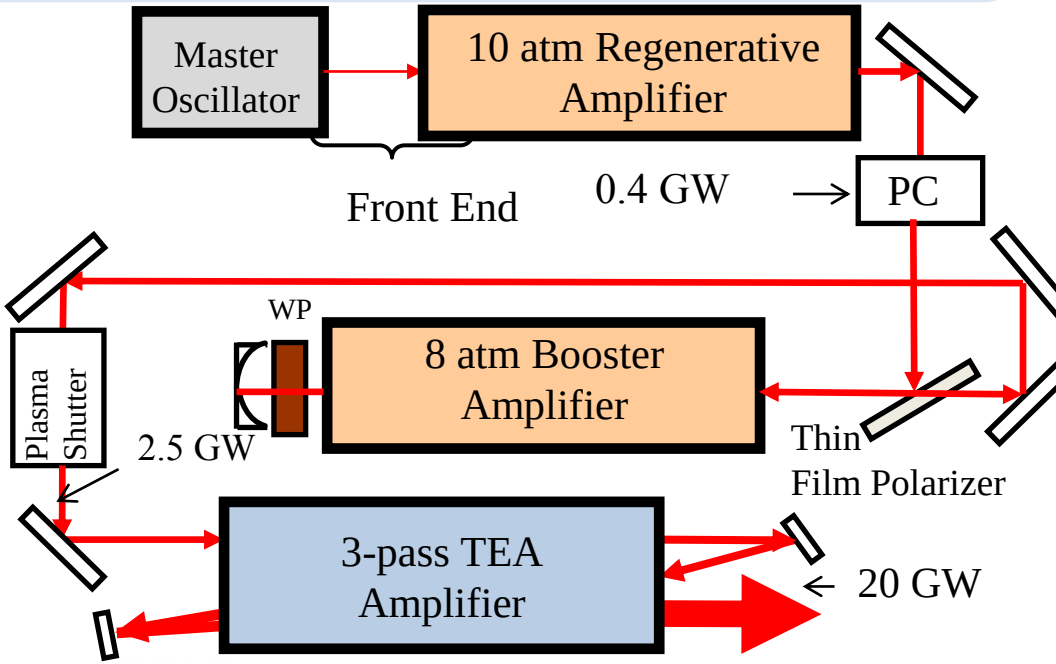
Equivalent to the broadening in a 10 atm laser

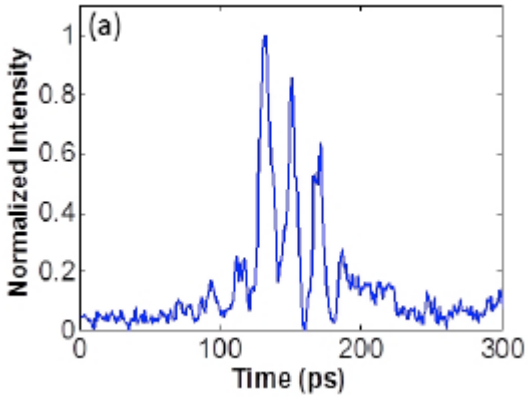
$$\Delta\nu_{Total} = \Delta\nu_{Pressure} + \Delta\nu_{Field}$$

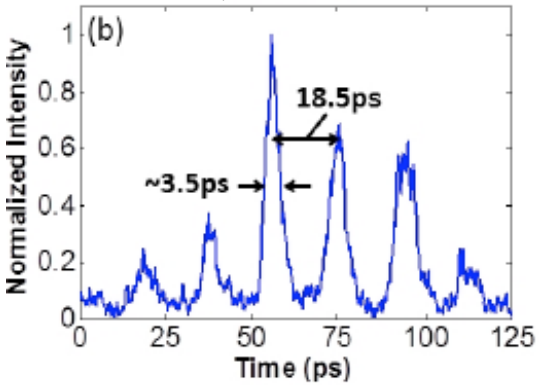


Neptune Laboratory's High Repetition Rate CO_2 Laser System

- System parameters
  - 1 Hz repetition rate
  - 20 GW peak power
  - 3 ps pulse duration
  - 10.6 um wavelength







S. Ya. Tochitsky, et. al. Amplification of Multi-Gigawatt 3ps Pulses in Atmospheric CO_2 Laser Using ac Stark Effect Opt. Express **20**(13), 13762–13768 (2012).

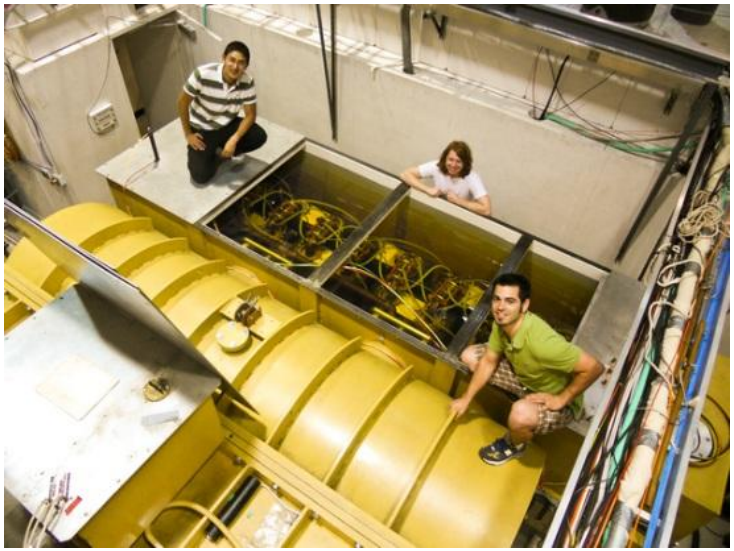
Neptune Laboratory's High Repetition Rate CO_2 Laser System

15 TW, 3 ps at

1 shot per 300 seconds

20 GW, 3 ps at

1 shot per second



Scalable both in repetition rate (100 Hz) and in energy (100 J)

Self-phase modulation of intense mid-IR pulses in a hollow gas-filled waveguide

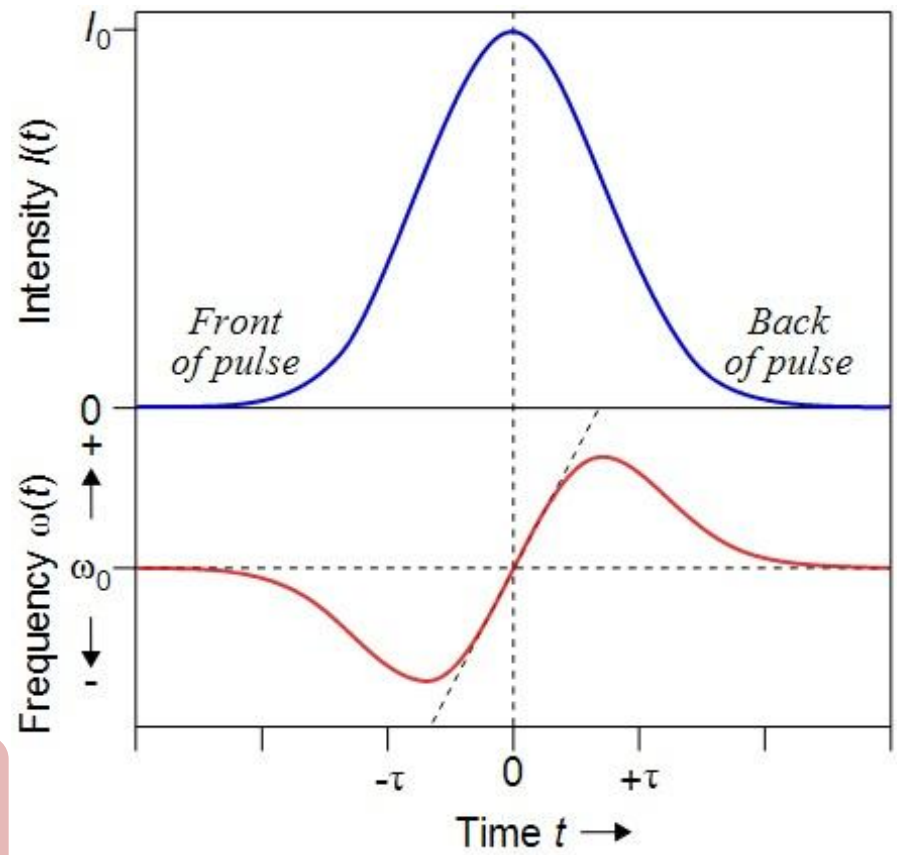
Self-phase modulation

$$\Delta n = n_2 I$$

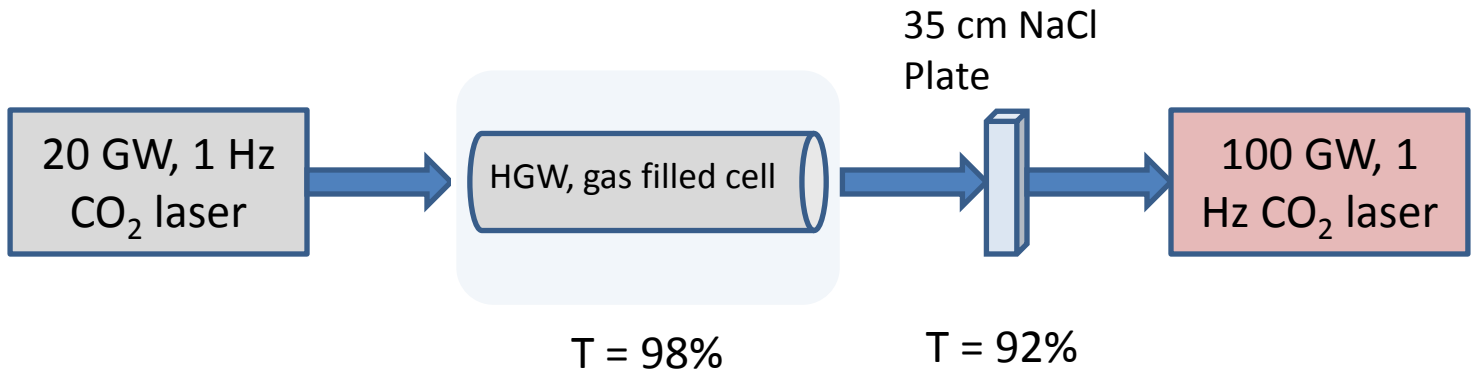
$$\phi(t) = \omega_0 t - n k_0 z$$

$$\omega_i(t) = \omega_0 + k_0 n_2 L \ \partial I / \partial t$$

SPM acts to increase the pulse's bandwidth



Pulse compression after self-phase modulation



Using the bandwidth created through SPM the pulses can be compressed to reach peak powers of 100 GW in 600 fs pulses

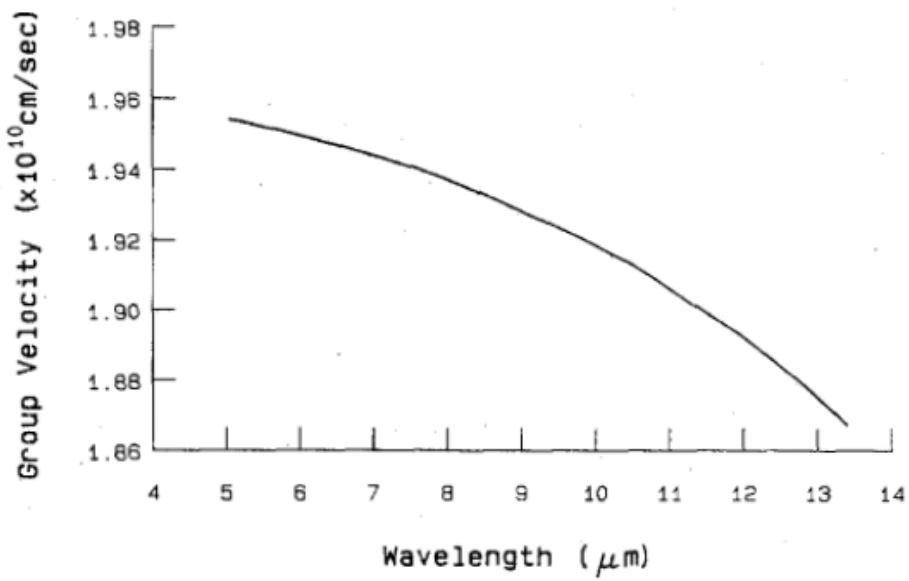
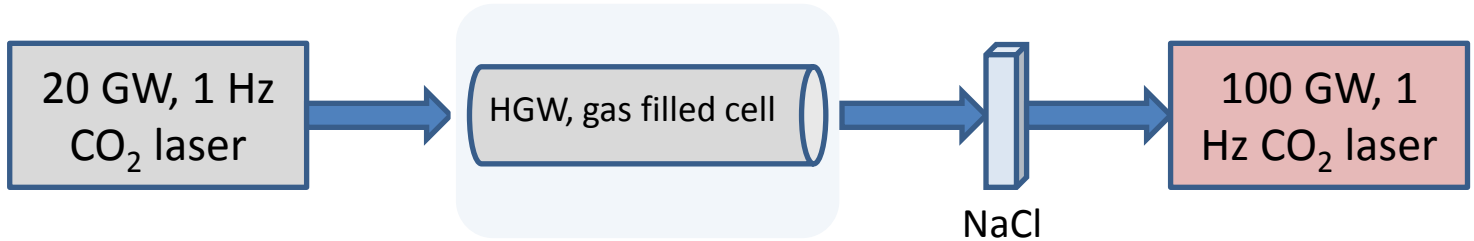
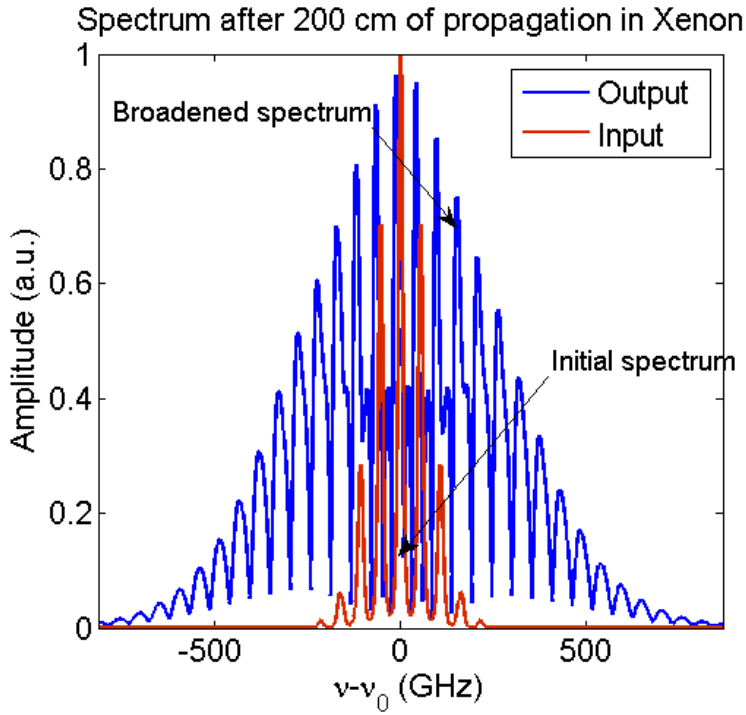
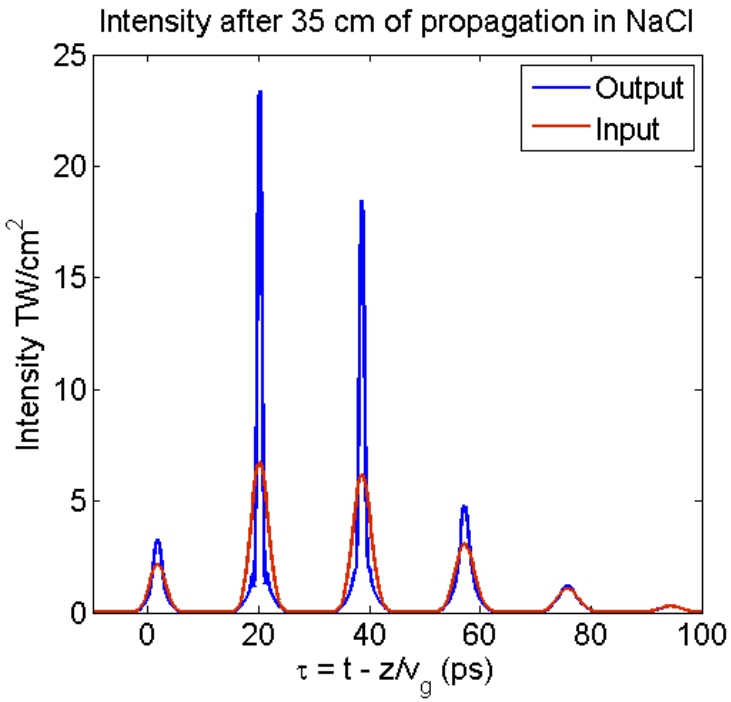


Fig. 15. Group velocity plotted as a function of wavelength for NaCl.

A. E. Siegman, *Lasers* (University of Science Books, Mill Valley, 1986).
P.B. Corkum, IEEE J. Quantum Electron. **21** (3), 216-232 (1985).







Propagation through Xe provides a factor of 5 increase in bandwidth and linearizes the chirp

Propagation through NaCl compresses the pulses down to ~ 650 fs, corresponding to a power of 100 GW

Assuming an input intensity of $\approx 6\ TW/cm^2$

$$n_2|Xenon = 7 \cdot 10^{-7} cm^2/TW$$

A. Couairon, *et. al.*, Phys. Rev. A. **77** (2008)

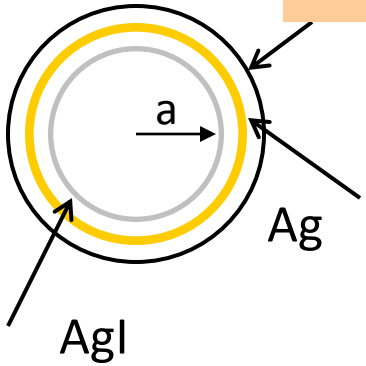
V.M. Gordienko, V.T. Platonenko and A.F. Sterzhantov, *Quant. Elect.* **39**(7), 663-668 (2009).

A. E. Siegman, *Lasers* (University of Science Books, Mill Valley, 1986).

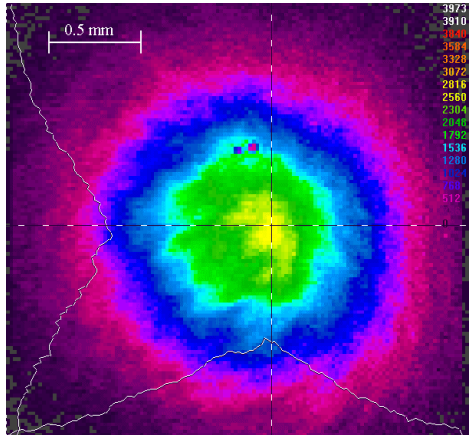
Agrawal, Nonlinear Fiber Optics. Academic Press

Guiding of 10um light in a hollow glass waveguide (HGW)

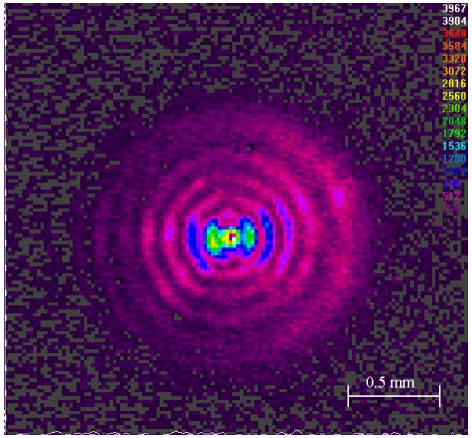
Silica hollow glass waveguide (HGW) - a=500 μm, L=30 cm



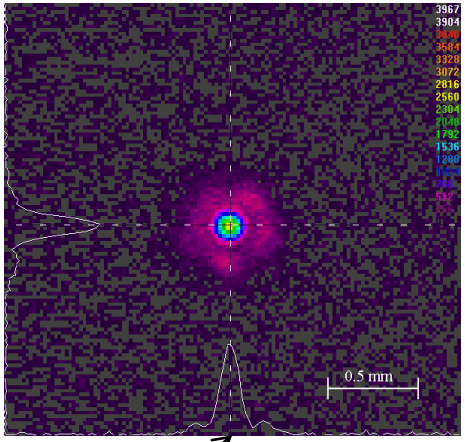
No Waveguide



a=500 μm



a=200 μm

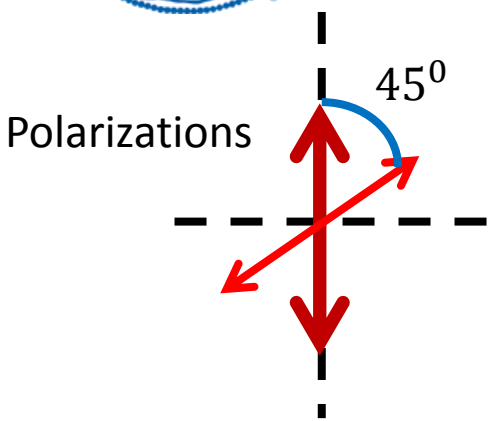


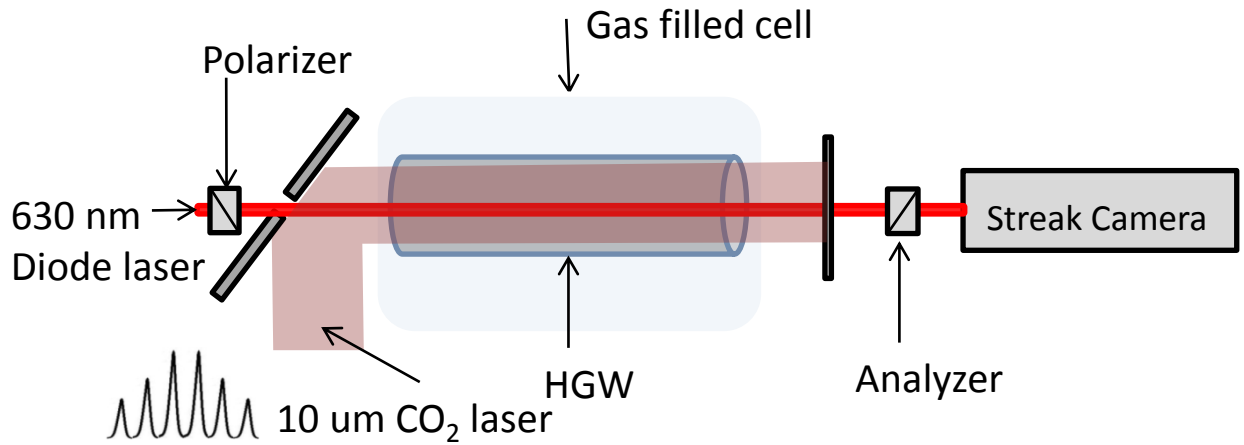
Coupling condition for EH_{11} mode: $\frac{w_0}{a} = 0.64$

Guiding intensities of > 10^{11} W/cm^2 over 300 mm (125ZR) with an energy transmission of >90 % in the air. Coupling efficiency is limited by the ionization induced refraction of the laser beam.

C. Sung, S. Ya. Tochitsky and C. Joshi. Guiding of 10 um laser pulses by use of hollow waveguides. Eleventh AAC Workshop, 512-518. (2004)

Measuring the nonlinear index of refraction via the Kerr effect in a HGW





<u>Measurement of transient birefringence related to n_2 only</u>

- Experiment with a pressure of ~ 100 torr to avoid ionization
- Using a power below the critical power for self-focusing yet guiding the beam externally using a HGW
- 632 nm probe, 10um pump

Fit transmission as a function of time using Malus's Law:

$$T(t) = A\sin^2[2.34 \cdot 10^6 \left(\frac{\pi L}{\lambda}\right) n_2 I_{pump}(t)]$$

Average n_2 over many shots and fit as a function of fill pressure

$$n_2(p) = n_{2atm}\left(\frac{p}{p_0}\right)$$

D.J. Haberberger, S. Ya. Tochitsky, and C. Joshi. 15 terawatt picosecond CO_2 laser system. Opt. Express **18**(17), 17865-17875 (2010) .
C. V. Filip, *et. al.* Applied Optics **41**(18), 3743-3747 (2002).

Conclusions

- We developed a 20 GW, 3 ps, CO_2 laser operating at 1 Hz
- Self-phase modulation in a waveguide can lead to 100 GW
- Such a source may be ideal for studies in advanced acceleration and radiation generation

Acknowledgements

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