Lecture 41. LIDAR Future Outlook

- What's new and what's happening out there?
- White-light lidar
- Future potentials and growing points

What's New and What's Happening?

❑ Rapid advancement of laser technologies (solid state, energy efficient, small volume and mass, long-life time):

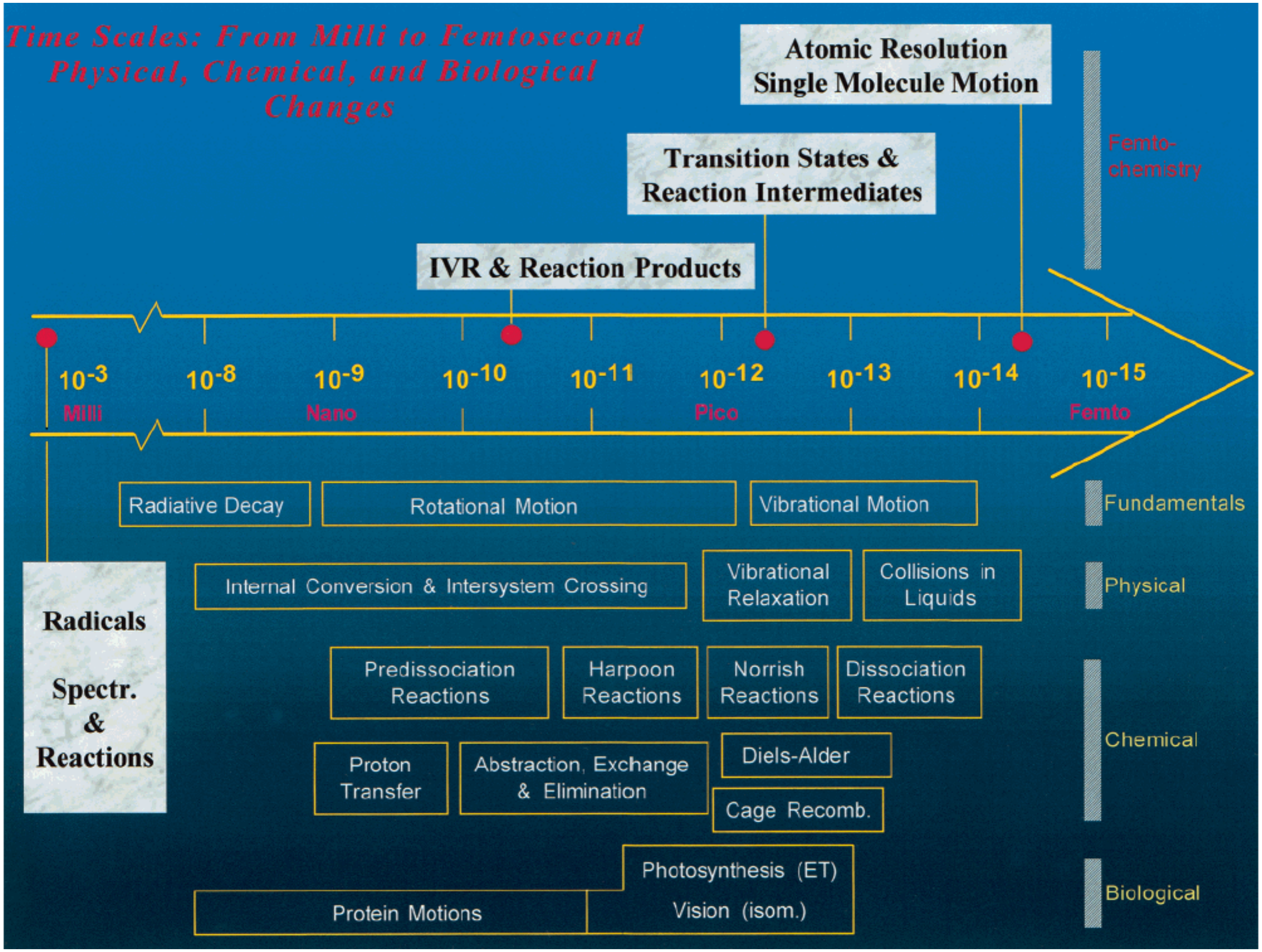
- External cavity diode laser (ECDL), Distributed Feedback (DFB) laser, Distributed Bragg Reflector (DBR) laser, Quantum-well or dot laser, Waveguide external cavity semiconductor laser (WECSL), etc.
- Diode-pumped Nd:YAG laser, Alexandrite laser, Fiber laser, Raman laser
- Optical parametric oscillator (OPO), Optical parametric amplifier (OPA),
- Frequency doubling or tripling, Frequency mixing, femtosecond laser, etc.

❑ Rapid development of new detectors, optics, electro-optics, computer, control, telescope, fiber, etc.

❑ New lidar technologies are being proposed and developed to improve the measurement accuracy, precision, resolution, range and capability as well as the mobility to enable new scientific endeavors. Lidar applications are constantly being renewed. Lidar developments and observations are being actively pursued worldwide. This will expand the lidar arena.

❑ The whole atmosphere lidar concept has been discussed for profiling wind and temperature from ground to 120 km. The space-borne middle atmosphere lidar concept is on the horizon. More lidars will be spaceborne in the near future.

Laser Spectroscopy versus Time Scale

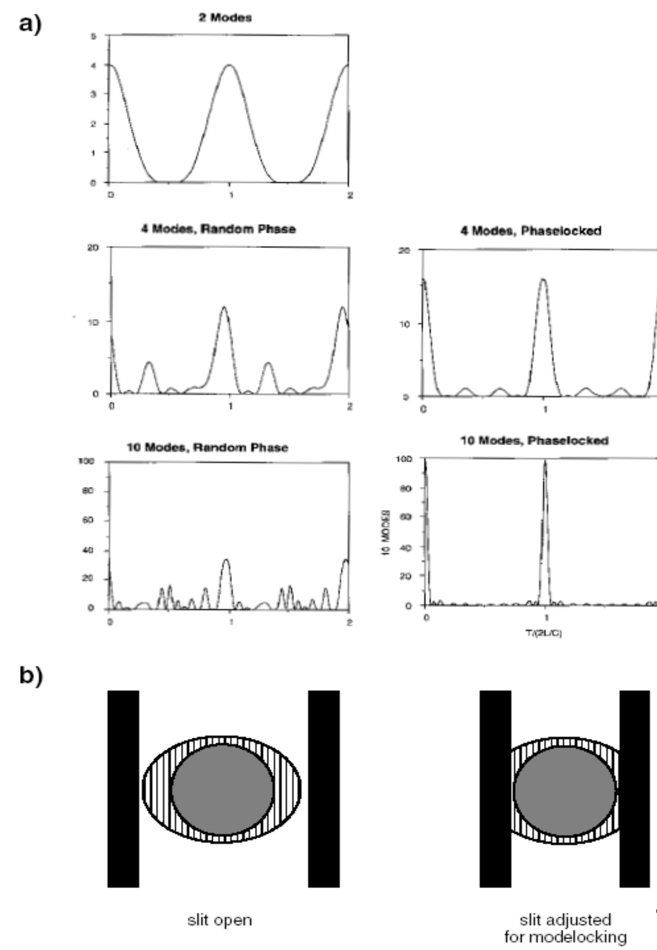


Ahmed H. Zewail, *J. Phys. Chem. A* **2000,** *104,* 5660-5694

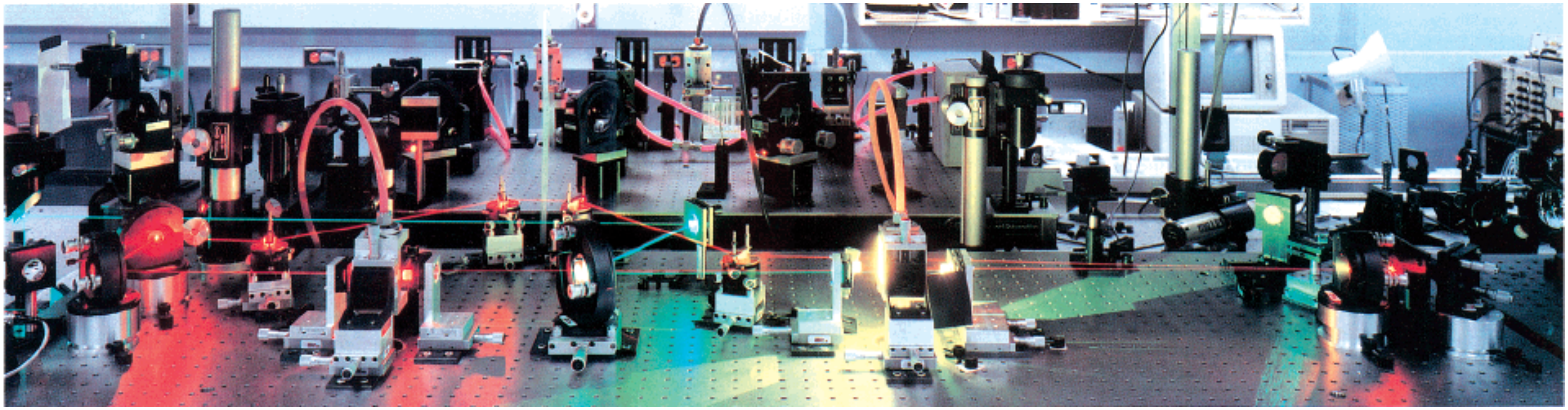
Generation of Short Laser Pulses

1. Short laser pulse introduced by gain material About μs
2. Q-Switched laser (Q quality factor) About ns
   Keep low Q to prevent laser power build up, and then suddenly increase Q in a very short period to build up laser.
   Spinning mirror, Pockels cell…
3. Cavity Dumping About ns
   Keep high Q, keep high power lasing.
   Kick out the laser in a very short period.
   Pockels cell, Acoustic-optical Switch…
4. Mode Locking Laser About ps
   Active, Passive, Synchronous Pumping
5. Create femto-second laser pulse
   (optical process)
   Colliding-pulse mode locking
   Kerr lens mode locking

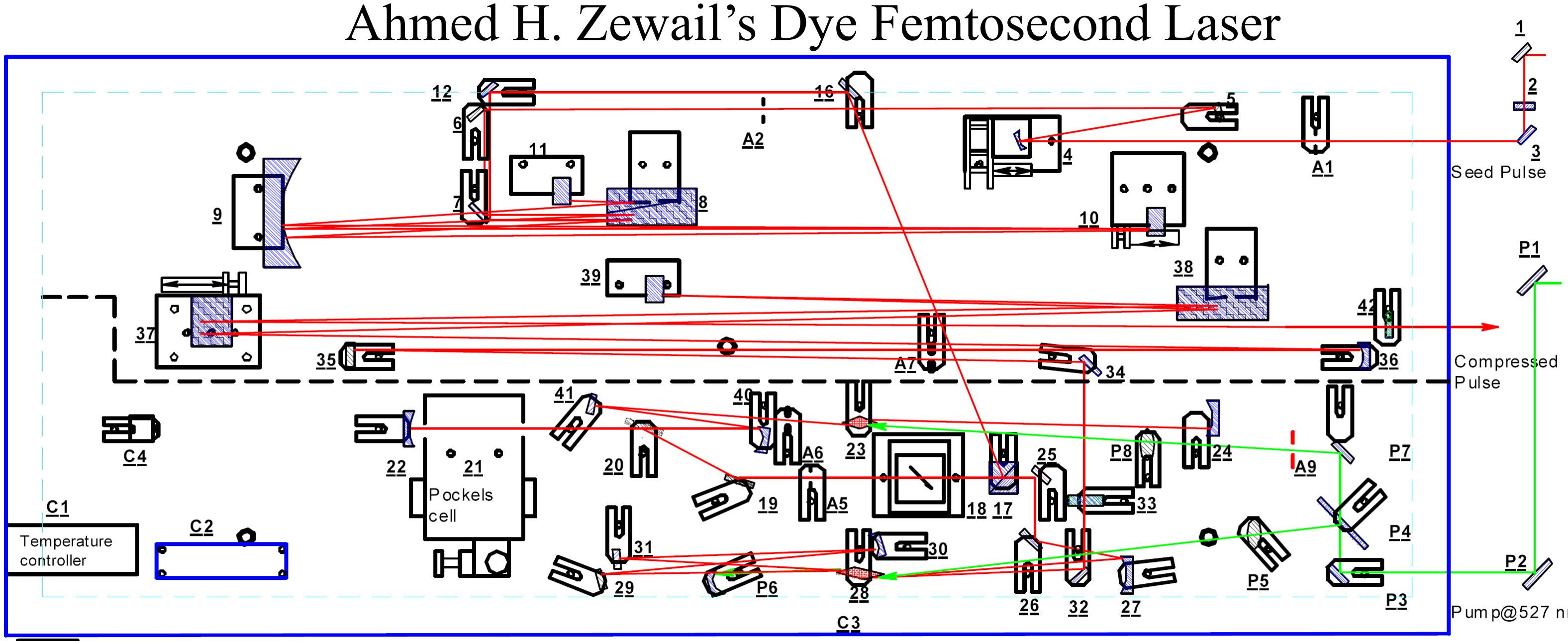
10-fs full width at half-maximum (FWHM) Gaussian pulse centered at 800nm has a bandwidth of 94nm



Femto-Second Laser



Ahmed H. Zewail's Dye Femtosecond Laser



QUANTRONIX Titan Ti:Sapphire Amplifier

White-Light Lidar

- The atmospheric and target lidars we discussed in the lidar class, provide range resolved information of temperature, wind, trace gases and aerosols. However, they are usually limited to the detection of only one gaseous substance at a time, and does not allow the remote determination of aerosol chemical composition.
- Long-path optical absorption methods like Fourier-transform infrared spectroscopy (FTIR) or differential optical absorption spectroscopy (DOAS) simultaneously yield precise concentration data of a large group of atmospheric constituents from the absorption of light from a broadband source, like the Sun or the Moon or lamp, across the atmosphere. But they do not give range information.
- Combination of the range resolution of lidar with the multi-component analysis capability of DOAS or FTIR is apparently very attractive for environmental, weather, and climate studies. This requires the generation of a remote white-light atmospheric lamp, which could be placed as needed in the atmosphere.
- This leads to the white-light lidars based on femto-second lasers:

1) High-power fs laser pulses are adequately chirped to compensate group-velocity dispersion in the air, leading to the coincidence of the pulse temporal focus with its geometrical focus. Thus, the laser pulses create a plasma spot and generate white-light filament in the atmosphere at a predetermined distance.

2) The white-light covers a broad spectrum range (UV to IR), enabling the detection of various constituent absorptions when the receiver equipped with time-gated spectral analyzers (e.g., time-resolved high-resolution spectrometers).

Filament and White-Light Generation

- Kerr self-focusing effect $n(I) = n_0+n_2I$
- Multiphoton ionization (MPI) and plasma defocusing effect
- A remarkable behavior is observed in air: both Kerr self-focusing and plasma defocusing effects exactly compensate and give rise to self-guided quasi-solitonic propagation. The laser beam is first self-focused by Kerr effect. This focusing increases the beam intensity and generates a plasma by MPI, which in turns defocusing the beam. The intensity then decreases and plasma generation stops, which allows Kerr re-focusing to take over again.
- This dynamic balance between Kerr effect and plasma generation leads to the formation of stable narrow structures called "filament".
- The super-continuum spectra of filament is generated by self-phase modulation: $n(t) = n_0+n_2I(t)$, leading to a time-dependent phase shift, thus new frequencies. This induces strong spectral broadening about the carrier freq ω_0.

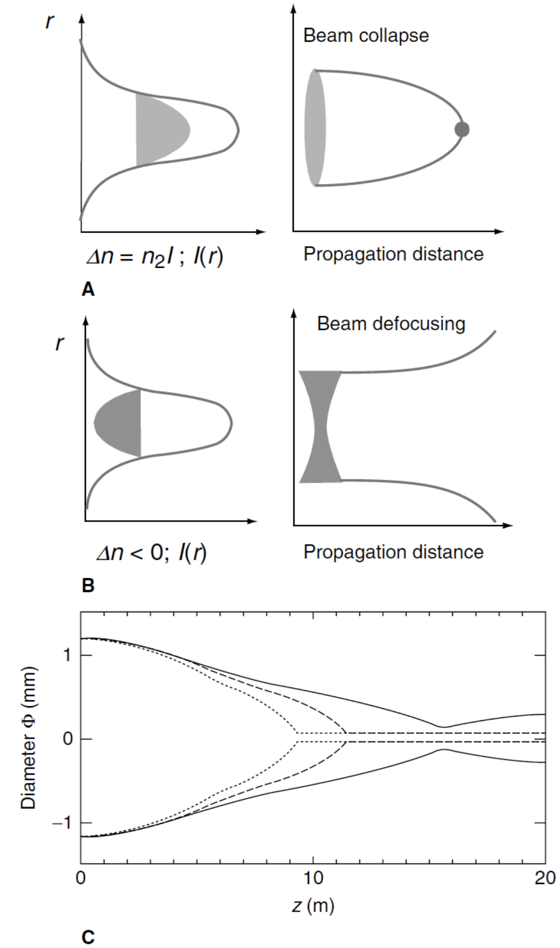
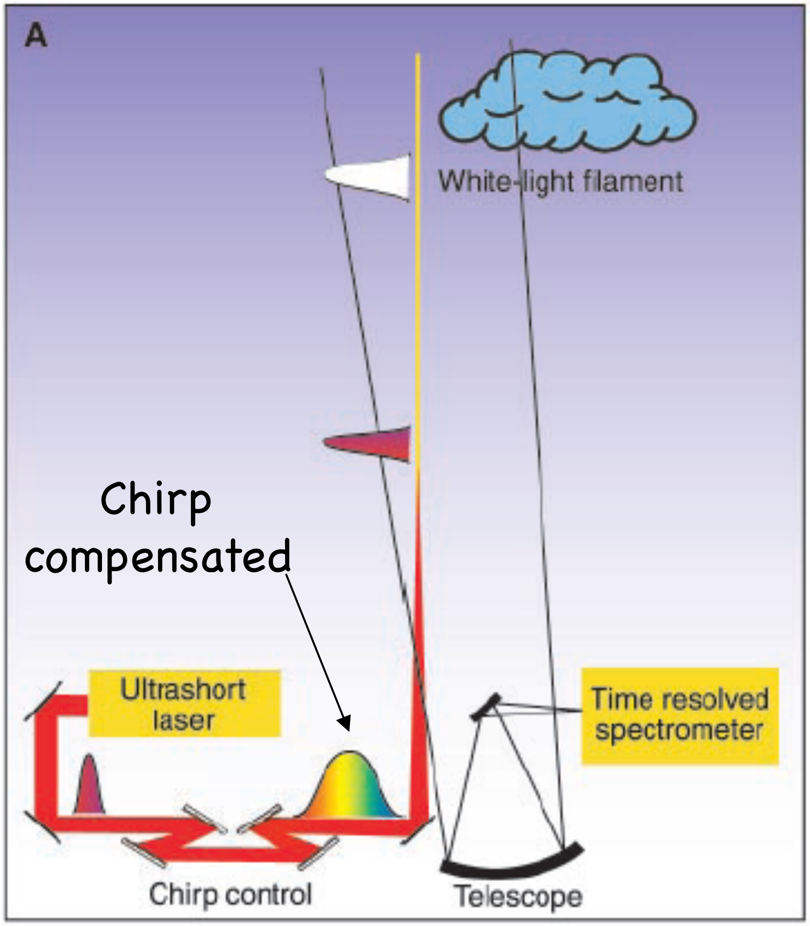


Figure 2.4 Principle of the focusing Kerr lens (A) and the defocusing plasma lens (B). A balance of both effects results in self-guided high-intensity (10^{13} to 10^{14} W/cm^2) filaments with diameters in the range of 100 μm. (C) Theoretical calculation of the propagation of fsec-pulses. The curves show the evolution of the beam diameter as a function of the propagation distance, considering strong (continuous lines), weak (dashed lines), and no (dotted lines) retarded Kerr effect. (Panel C from Chiron et al., *Eur Phys. J. D*, 6, 383, 1999. With permission.)

Femtosecond White-Light Lidar



Teramobile White-Light Lidar

Chirped pulses compensate GVD to form filamentation at a desired location R_0.

[Kasparian J. et al, *Science*, 301, 61, 2003]

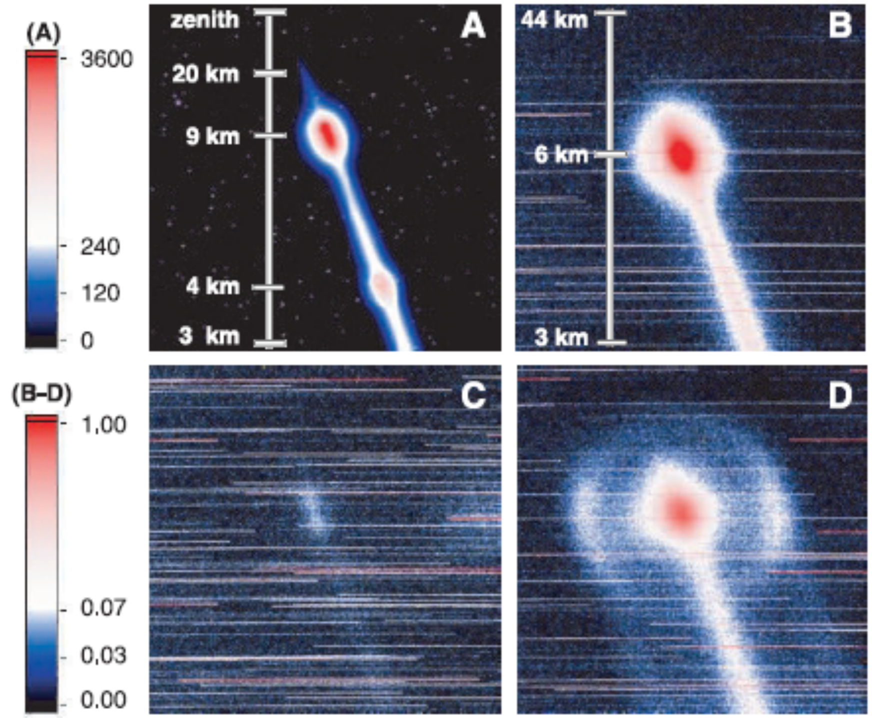


Fig. 1. Long-distance white-light propagation and control of nonlinear optical processes in the atmospheres. Images of the Teramobile fs laser beam propagating vertically were taken with the charge-coupled device camera at TLS observatory. (A) Fundamental wavelength, exhibiting signals from more than 20 km and multiple-scattering halos on haze layers at 4- and 9-km altitudes. (B to D) White light (385 to 485 nm) emitted by the fs laser beam. These images have the same altitude range, and their common color scale is normalized to allow direct comparison with that of (A). (B) With GVD precompensation. (C) Without GVD precompensation. (D) With slight GVD precompensation. The conical emission imaged on a haze layer is apparent.

White-Light Lidar: overcoming $1/R^2$

- Normal atmospheric lidars rely on the effect of optical backscattering of emitted light on atmospheric constituents. This leads to an unfavorable factor of $1/R^2$, where R is the range.
- When spectrally dispersed, the signal at the receiver is usually too weak for each wavelength.
- Fortunately, the white-light lidar shows a surprisingly strong backscattering. This makes fs-filaments in particular promising for lidar applications because it opens the perspective to establish a directional white-light source in the atmosphere radiating predominantly in the backward direction towards the receiver.

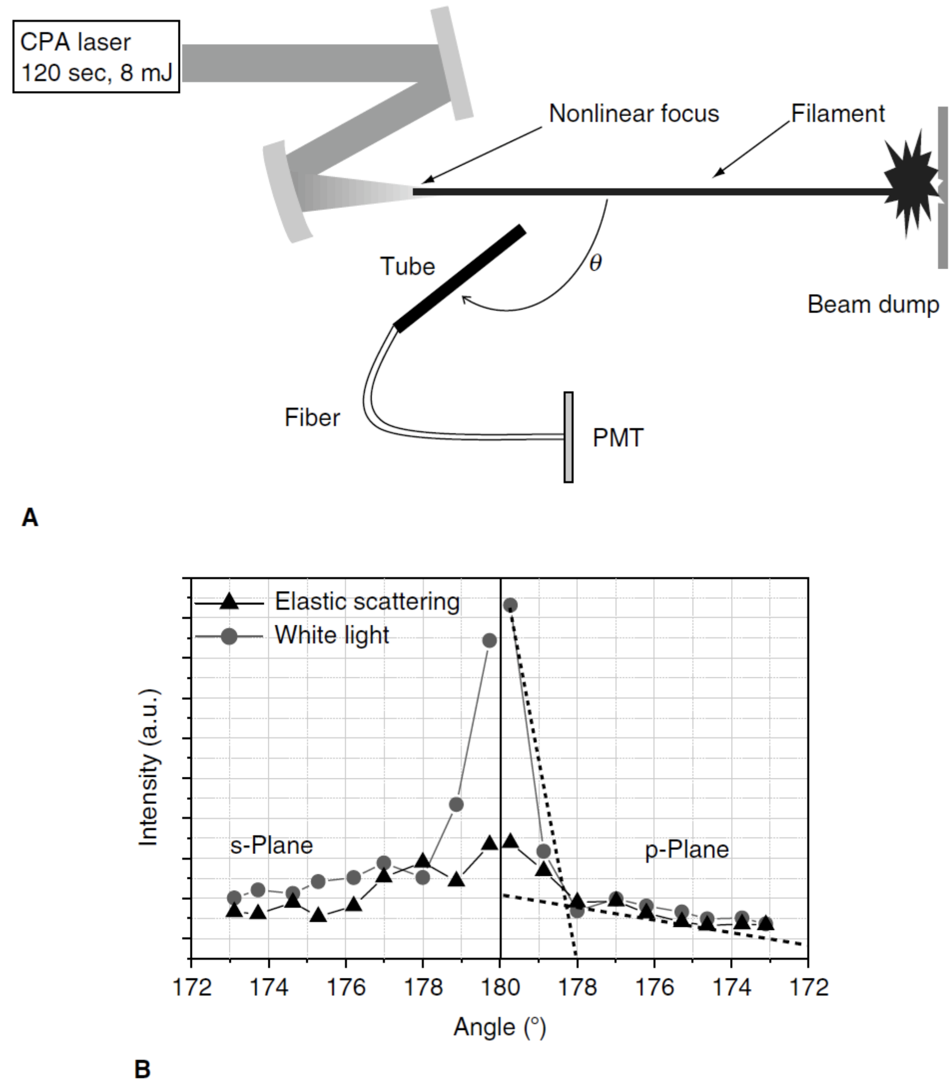


Figure 2.8 Self-reflection of the white-light supercontinuum: (A) experimental setup; (B) results around backscattering. (Derived from Yu J. et al., *Opt. Lett.*, 26, 533, 2001. With permission.)

White-Light Lidar: Example Results

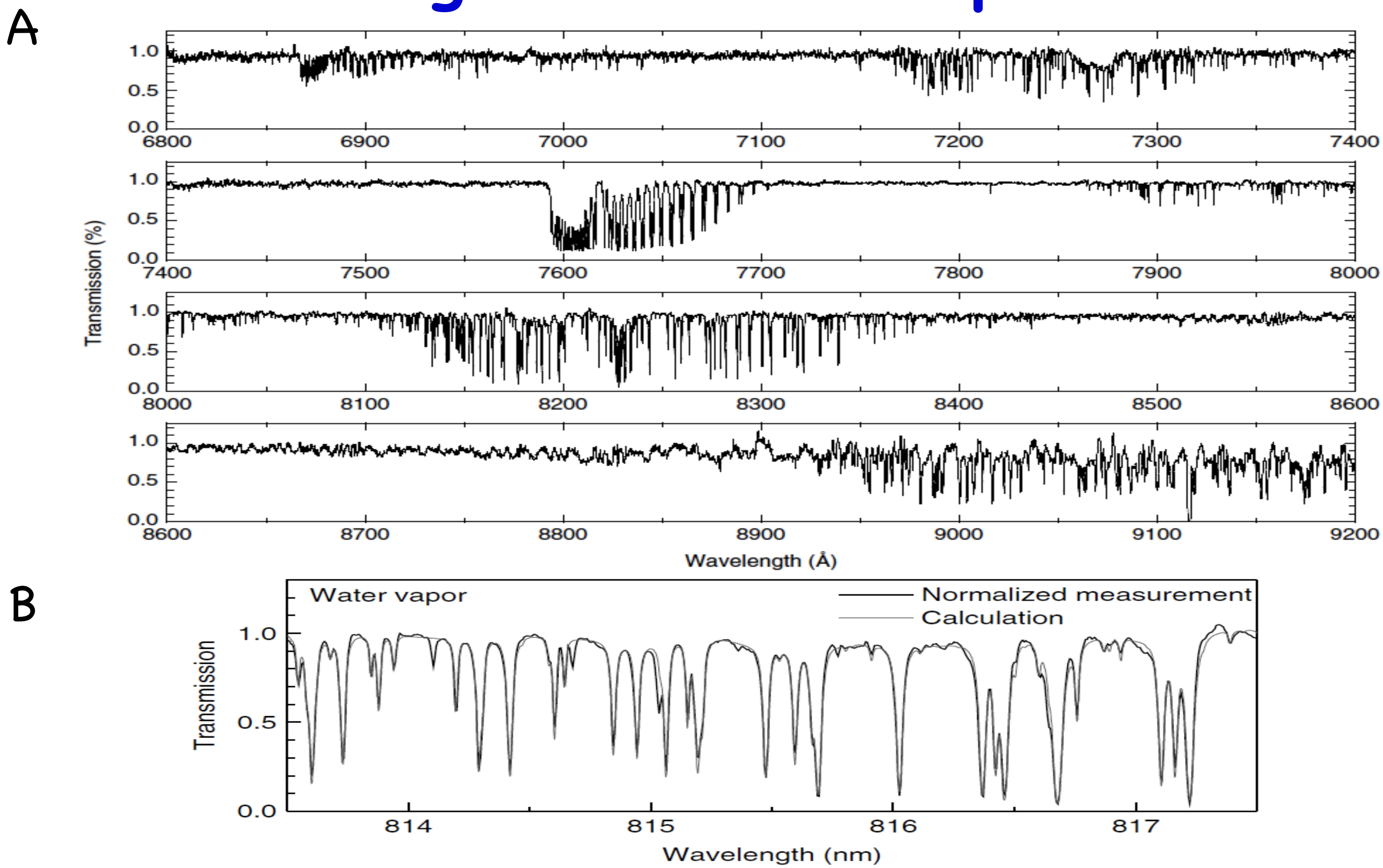


Figure 2.10 High-resolution spectrum of atmospheric absorption measured with the fsec-white-light lidar from an altitude of 4.5 km: (A) broad spectral range acquired in a single lidar acquisition (6000 pulses), showing several oxygen and water-vapor bands[5]; (B) section of the same spectrum with a fit based on HITRAN, to retrieve the averaged humidity. (Derived from Kasparian J. et al., *Science*, 301, 61, 2003. With permission.)

Future Potentials and Growing Points

- Lidar remote sensing is an advanced technology that is not only replacing conventional sensors in science study, environmental research, and industry application, but also creating new methods with unique properties that could not be achieved before.
- Lidar technology has been advanced dramatically in the past 20 years, owing to the new availability of lasers, detectors, creative people involved, and the demanding needs from various aspects.
- Potential growing points at this stage include

(1) Solid-state resonance fluorescence lidar for mobile deployment globally

(2) Extend measurement range into thermosphere and lower mesosphere

(3) Doppler, DIAL, HSRL, and Raman lidar for lower atmosphere research

(4) Fluorescence lidar and laser rangefinder for novel applications

(5) Aerosol/cloud lidar with Raman, polarization & multicolor detection capabilities

(6) Spaceborne lidar for more sophisticated lidar types

- Always keep eyes open for new potentials: principles, phenomena, effects, technologies to be applied in lidar and optical remote sensing.
- The exciting and growing lidar field is anxious for new "blood" - the creative, intelligent, diligent, and passionate young researchers.

Concluding Remarks for Lidar Class

- Thank you ALL for a success lidar class!
- I hope you have enjoyed the journey to learn about lidars, figured out the principles and details.
- I encourage you to continue the study of lidar through your own research work and make contributions to the lidar advancement and applications.
- Comments are welcome to help me make this lidar class a true excellence in the world!