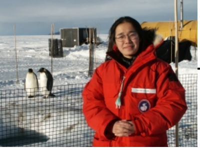
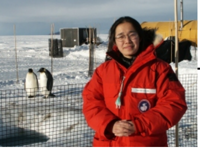
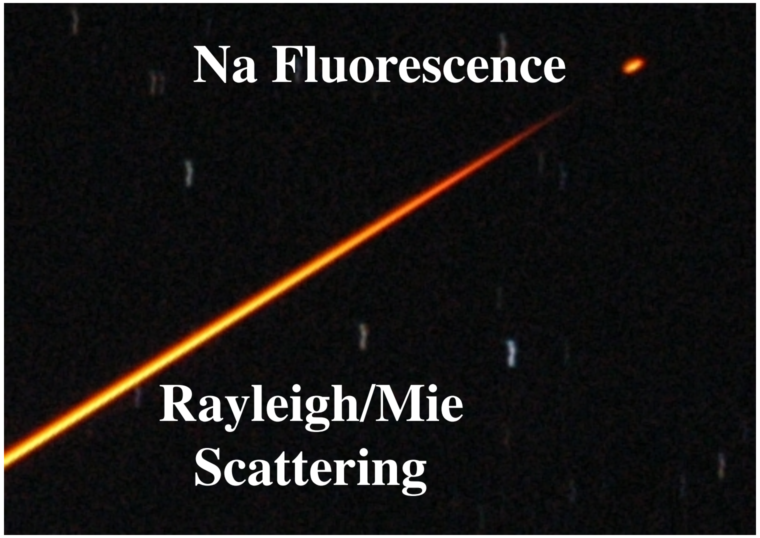


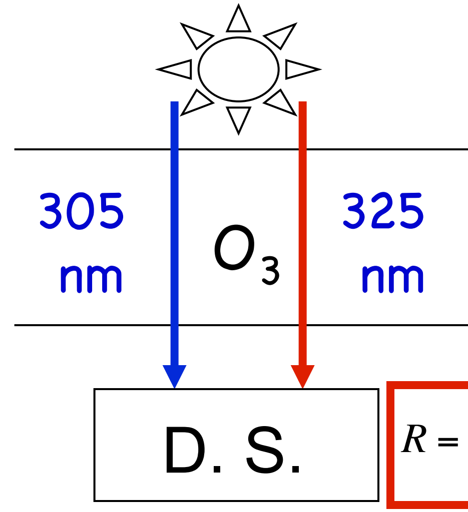
Lecture 43. White-Light Lidar & Lidar Future Outlook

- Motivations
- White-light lidar vs. femto-second laser
- What's new and what's happening out there?
- Future potentials and growing points

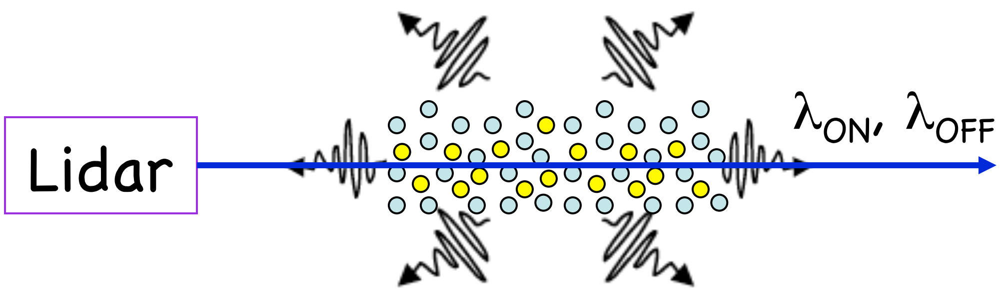


Motivations for White-Light Lidar



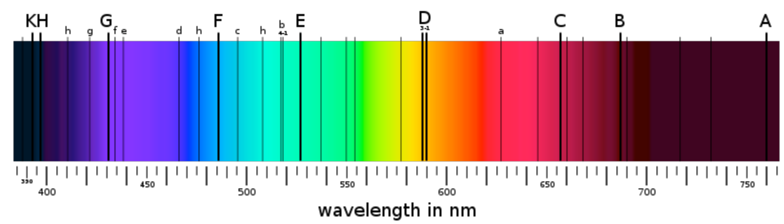


$$R = \frac{I_{325} - I_{305}}{I_{305}} \propto N_{O_3}$$

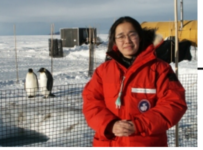


Atmospheric and LIF lidars provide range-resolved invaluable information of parameters like temperature, wind, species, etc., but usually limited to a certain species preknown.

Fraunhofer lines



FTIR or DOAS can measure many species simultaneously, but it's integrated, not range-resolved.

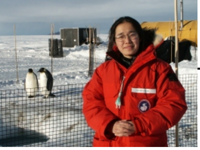


Motivations Continued

- 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.



Motivations for White-Light Lidar

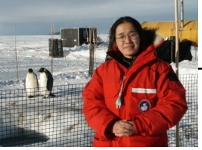
- The situations mentioned above lead to the white-light lidars based on femto-second lasers:

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.

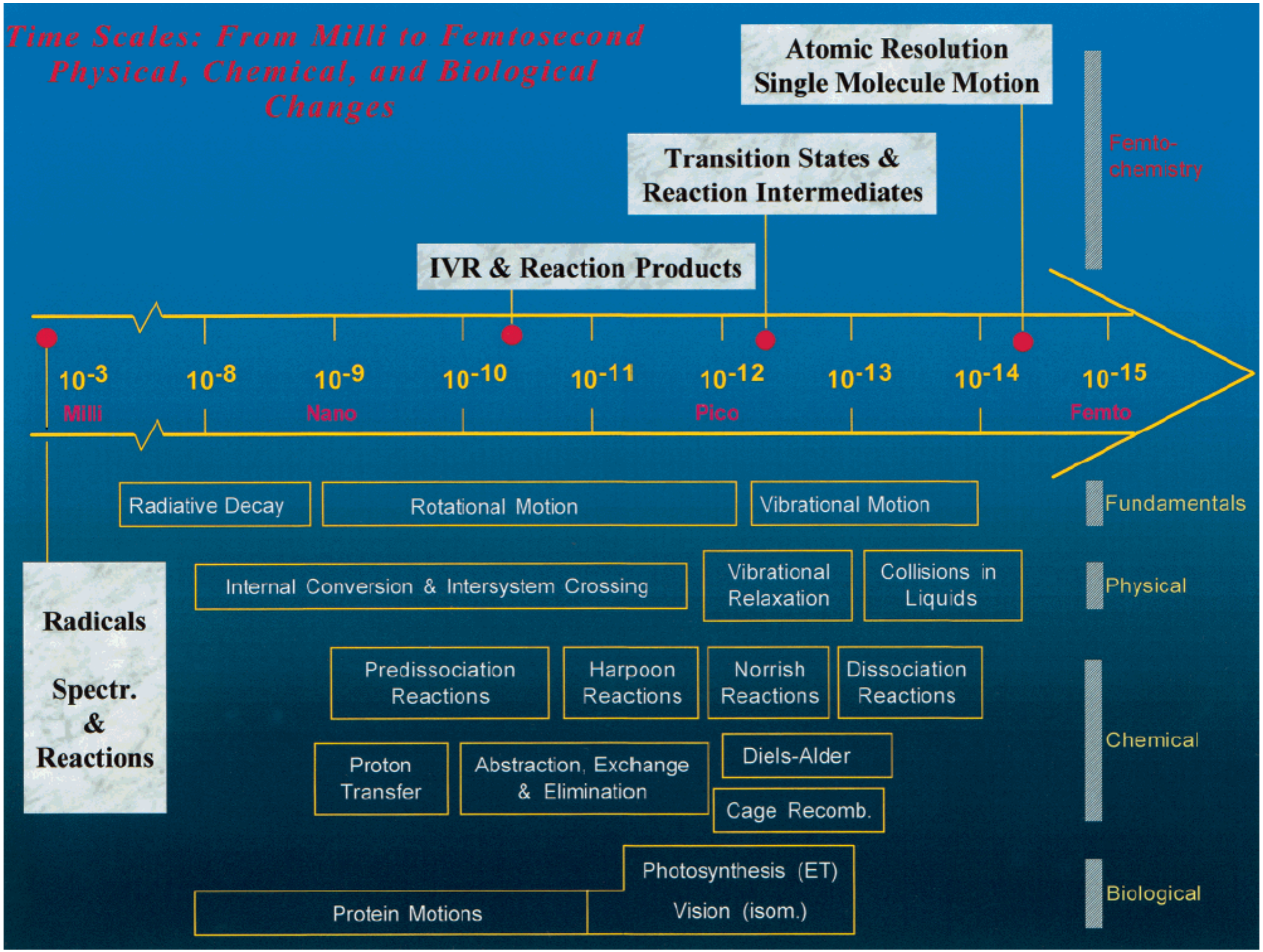
2) The white-light covers a broad spectrum range (UV to IR), enabling the detection of various constituent absorptions when the receiver equipped with time-gated spectral analyzers (e.g., time-resolved high-resolution spectrometers).

3) Optical frequency comb based on mode-lock femto-second lasers spans a very wide range spectrally, so is equivalent to white light.

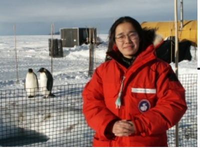
4) Millions of stable lasers simultaneously → white light lidar with better known laser sources for multiple species detection.



Laser Spectroscopy versus Time Scale



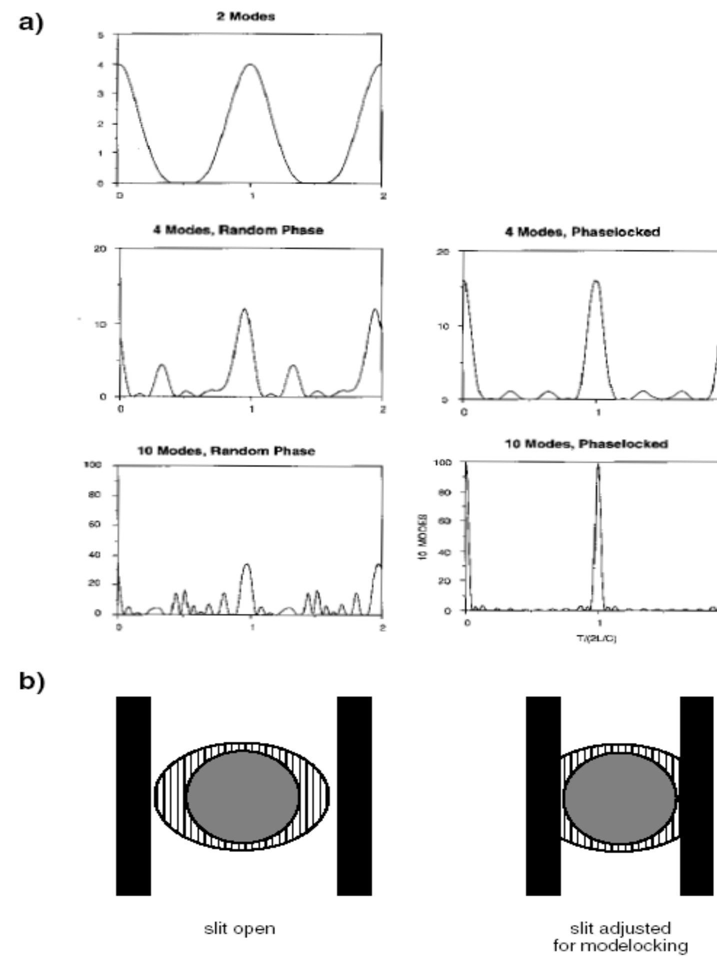
Ahmed H. Zewail, *J. Phys. Chem. A* **2000,** *104,* 5660-5694

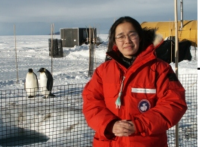


Generation of Short Laser Pulses

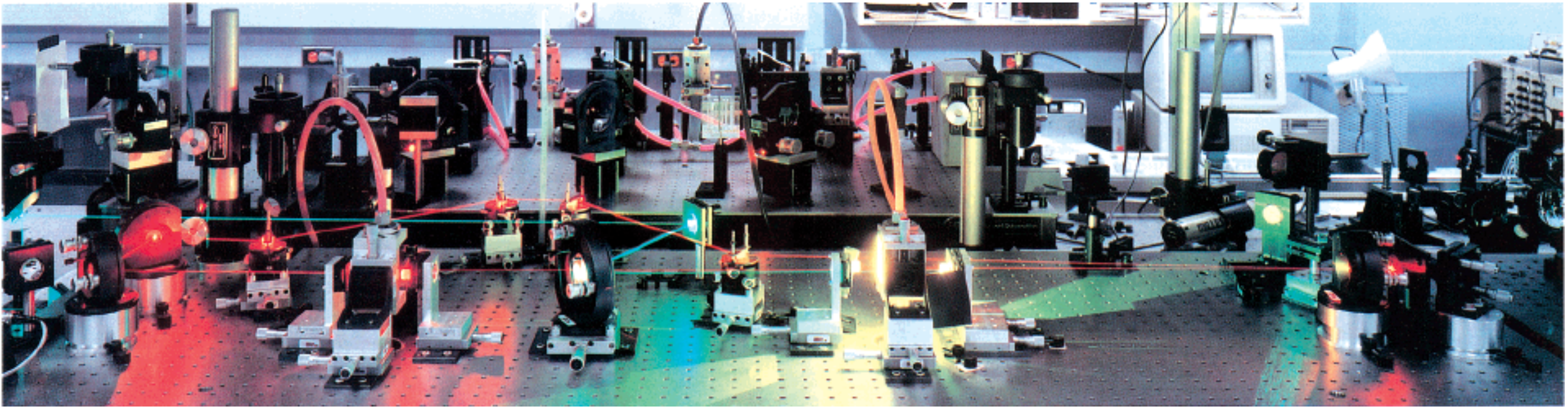
1. Short laser pulse introduced by gain material About μs
2. Q-Switched laser (Q quality factor) About ns
   Keep low Q to prevent laser power build up, and then suddenly increase Q in a very short period to build up laser.
   Spinning mirror, Pockels cell…
3. Cavity Dumping About ns
   Keep high Q, 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

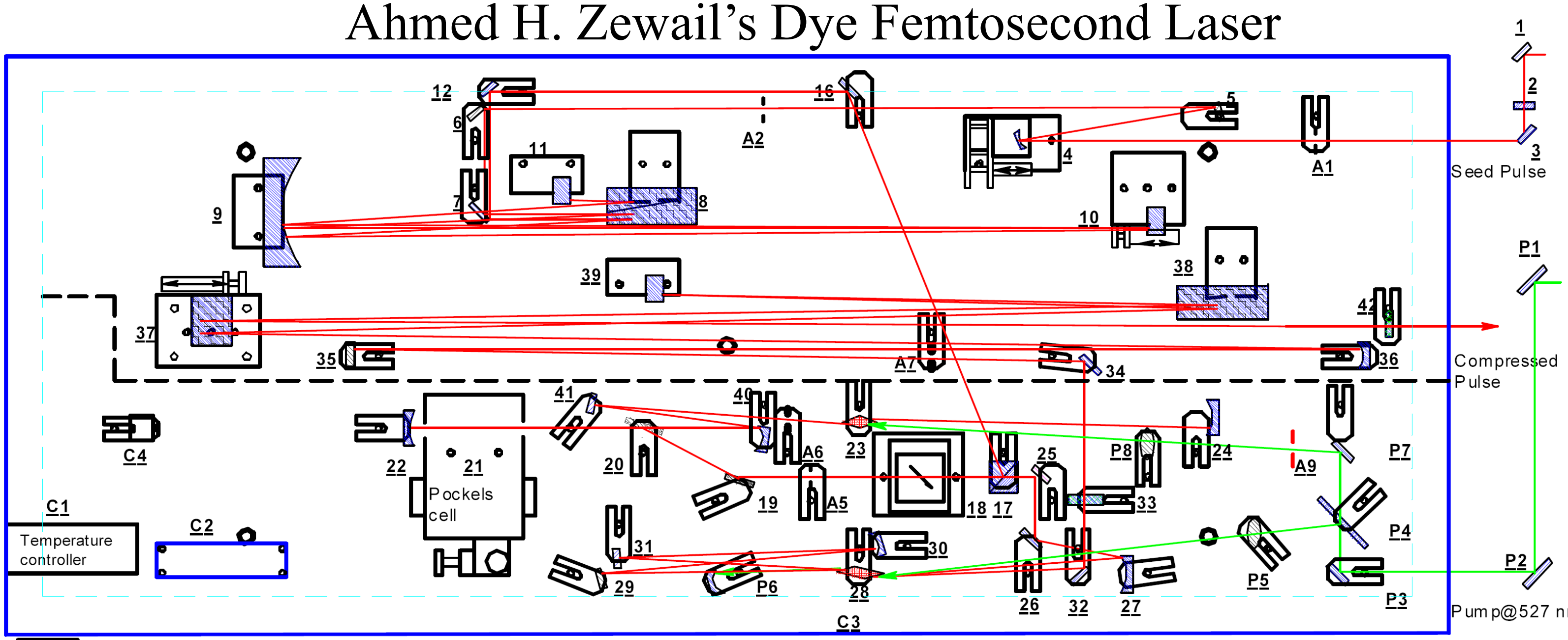




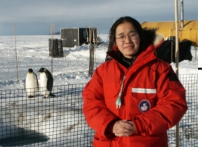
Femto-Second Laser



Ahmed H. Zewail's Dye Femtosecond Laser



QUANTRONIX Titan Ti:Sapphire Amplifier



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.

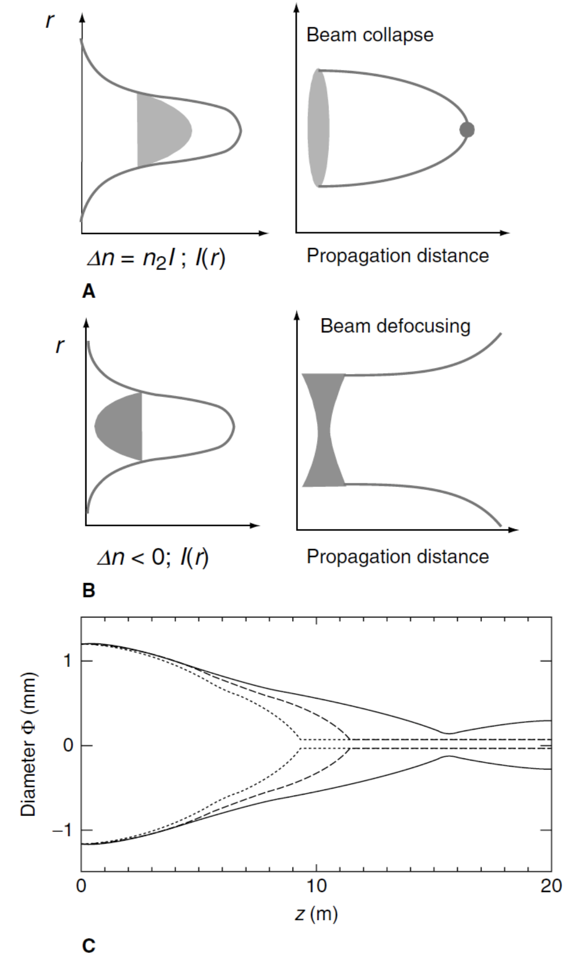
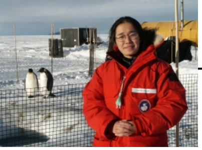
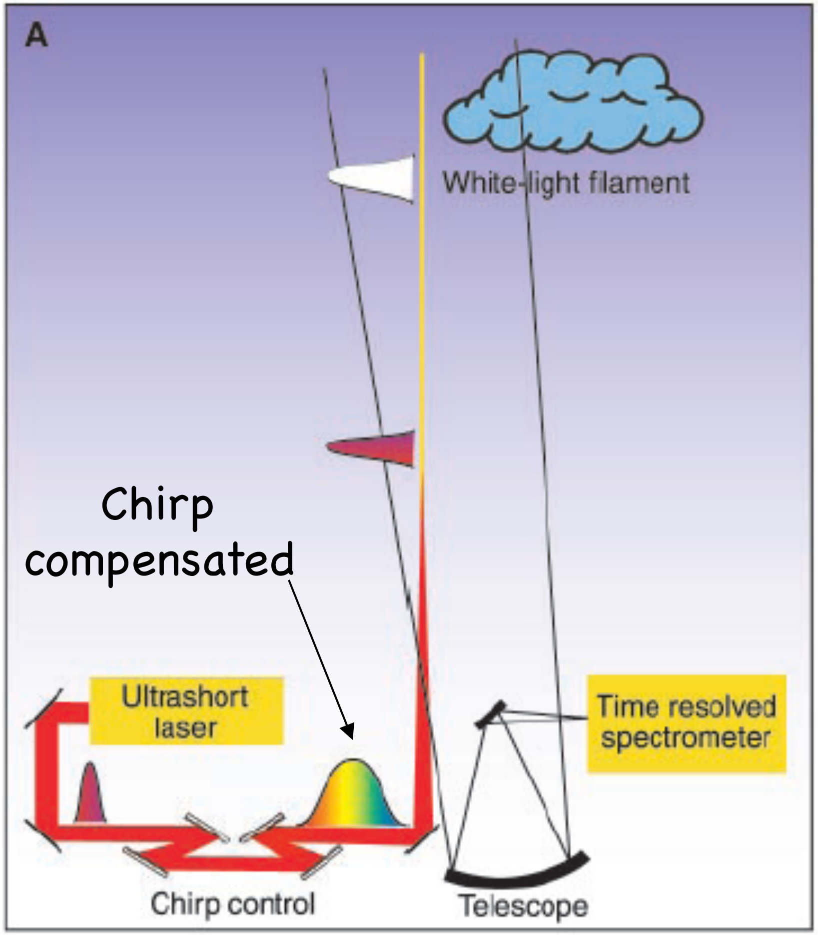


Figure 2.4 Principle of the focusing Kerr lens (A) and the defocusing plasma lens (B). A balance of both effects results in self-guided high-intensity (10^{13} to 10^{14} W/cm^2) filaments with diameters in the range of 100 μm. (C) Theoretical calculation of the propagation of fsec-pulses. The curves 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]

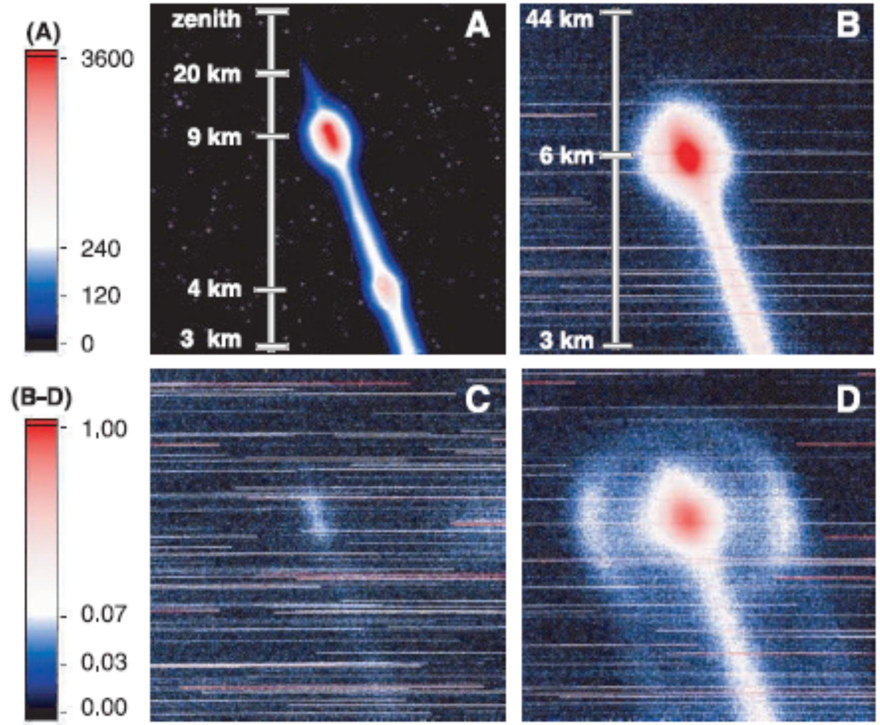
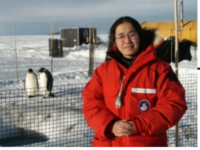


Fig. 1. Long-distance white-light propagation and control of nonlinear optical processes in the atmospheres. Images of the Teramobile fs laser beam propagating vertically were taken with the charge-coupled device camera at TLS observatory. (**A**) Fundamental wavelength, exhibiting signals from more 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.

Group-velocity dispersion



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.

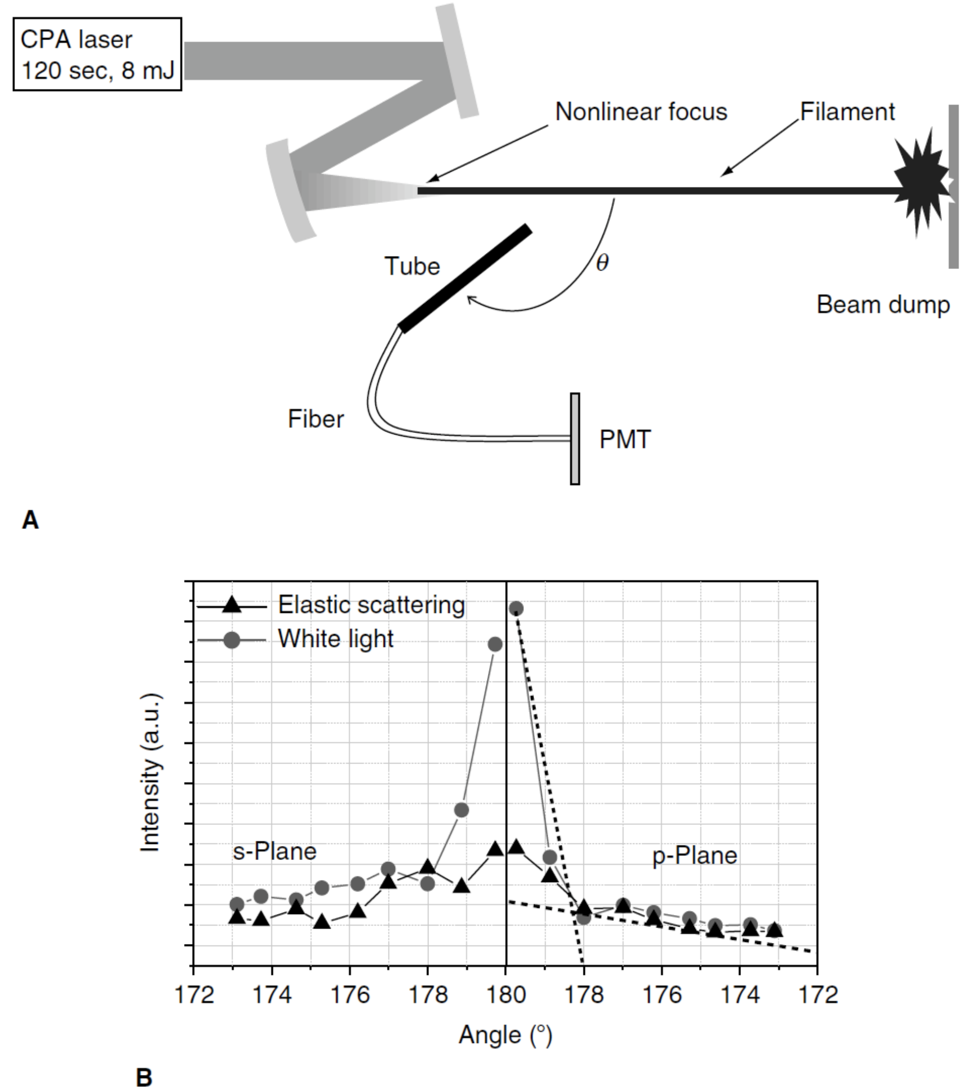
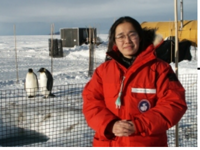


Figure 2.8 Self-reflection of the white-light supercontinuum: (A) experimental setup; (B) results around backscattering. (Derived from Yu J. et al., *Opt. Lett.*, 26, 533, 2001. With permission.)



White-Light Lidar: Example Results

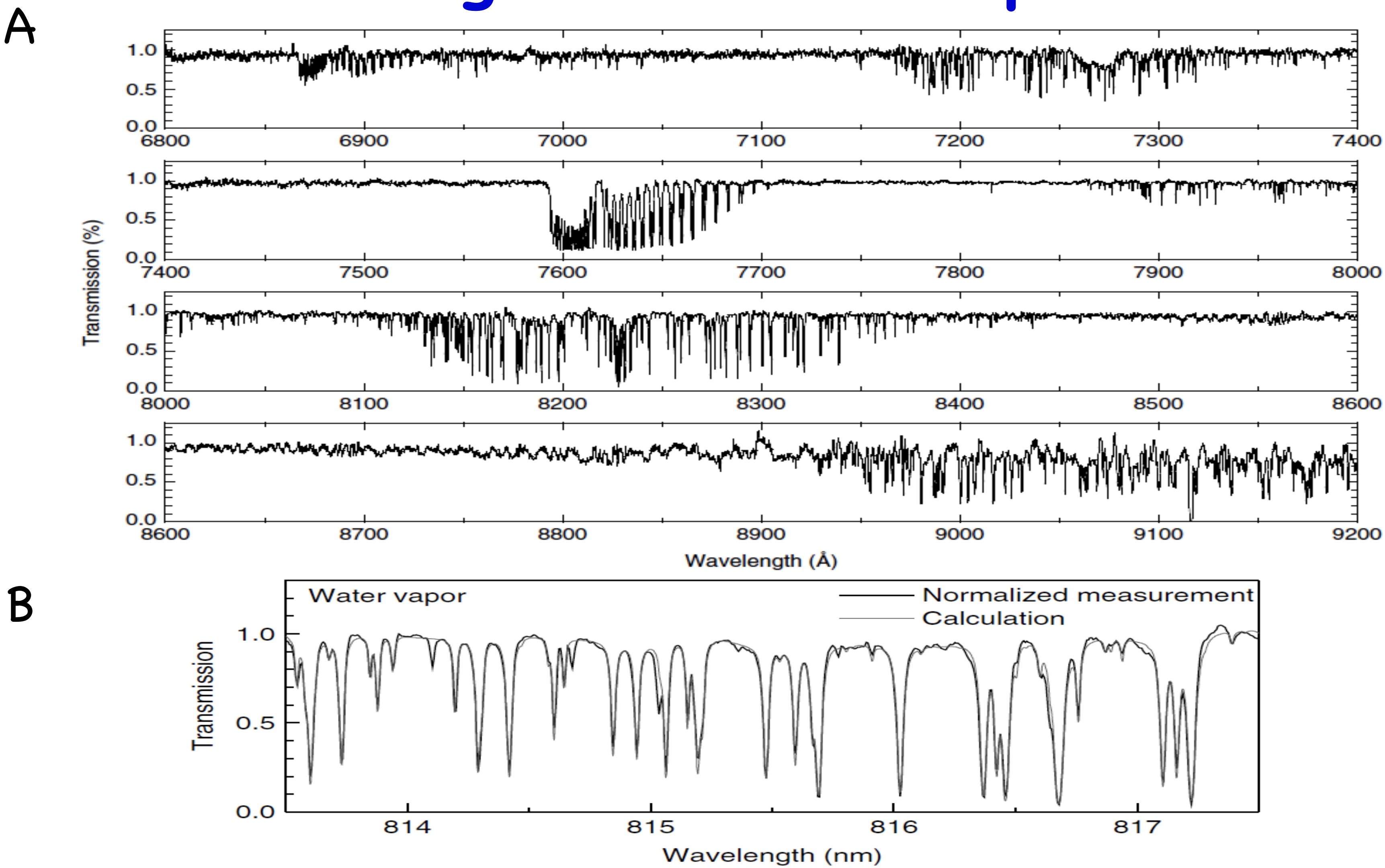
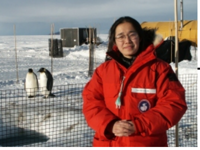


Figure 2.10 High-resolution spectrum of atmospheric absorption measured with the fsec-white-light lidar from an altitude of 4.5 km: (A) broad spectral range acquired in a single lidar acquisition (6000 pulses), showing several oxygen and water-vapor bands[5]; (B) section of the same spectrum with a fit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



Challenges: Still No Real Application ?

- Many demonstration papers have been published for white-light lidar, even in the journal of "Science", but so far we have not seen a real atmosphere application. In the last several ILRC conferences, white-light lidar did not have a strong show, or any papers. Why so?

- To my understanding, it is most likely due to the difficulties in the quantitative determination and analysis of the species and their concentrations.

- Challenges may come from several different aspects:

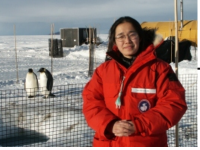
1) How much people can control the filament and white light generation, and how accurate people know the intensity and spectrum of the white light generated? How will the change in the atmosphere transmission affect the filament?

2) It's still challenging to achieve the range-resolved measurements, because the absorption is still an integration of the optical path. The filament/white light source must be placed at different ranges to derive the range-resolved info.

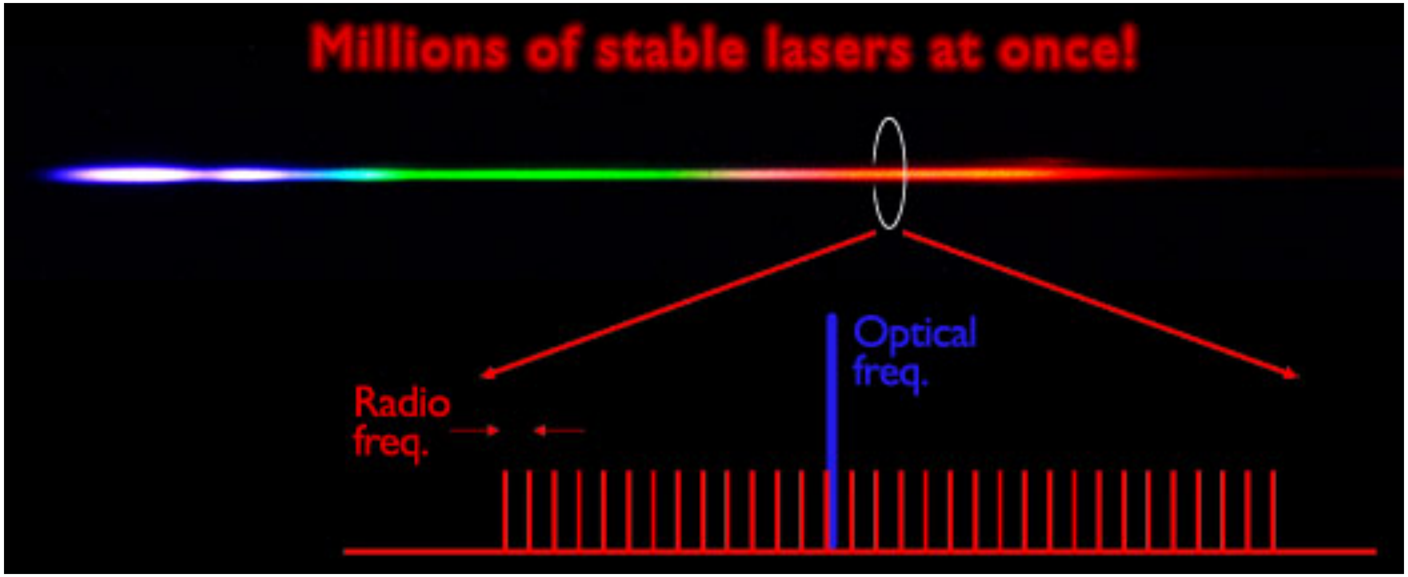
3) Time-resolved spectrum analysis demands fast detectors and data processing.

4) Interference among multiple species ???

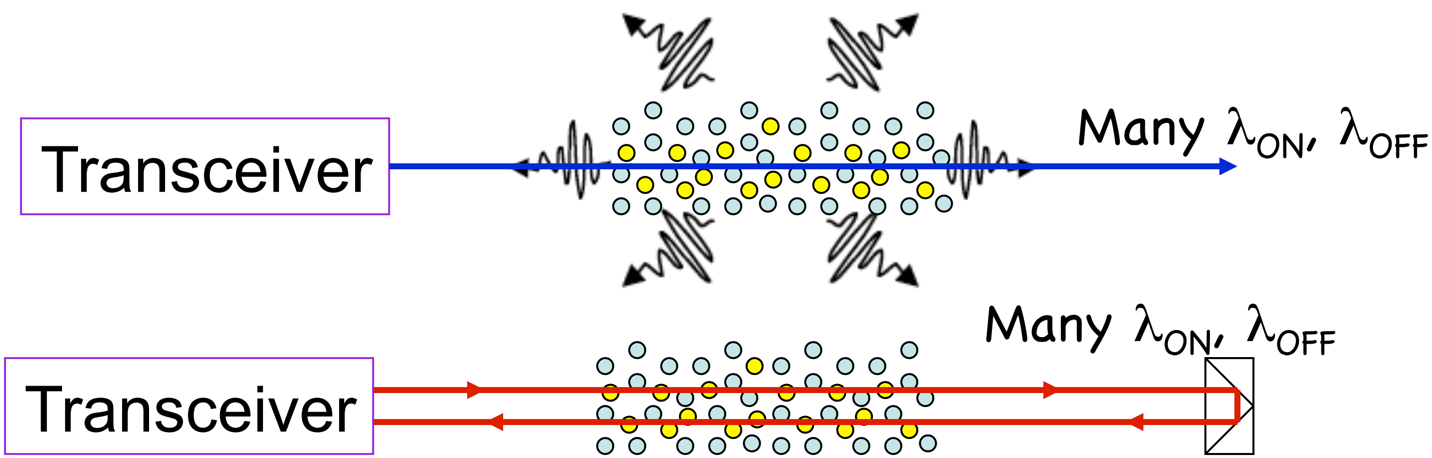
- However, white-light lidar is an attractive concept and worth further/future investigations. The filament idea is equivalent to move a spectral lamp from the lab into the atmosphere, but it is incoherent light source – not easy to quantify.

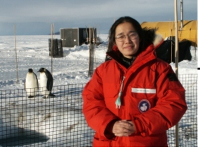


White-Light Lidar with Frequency Comb

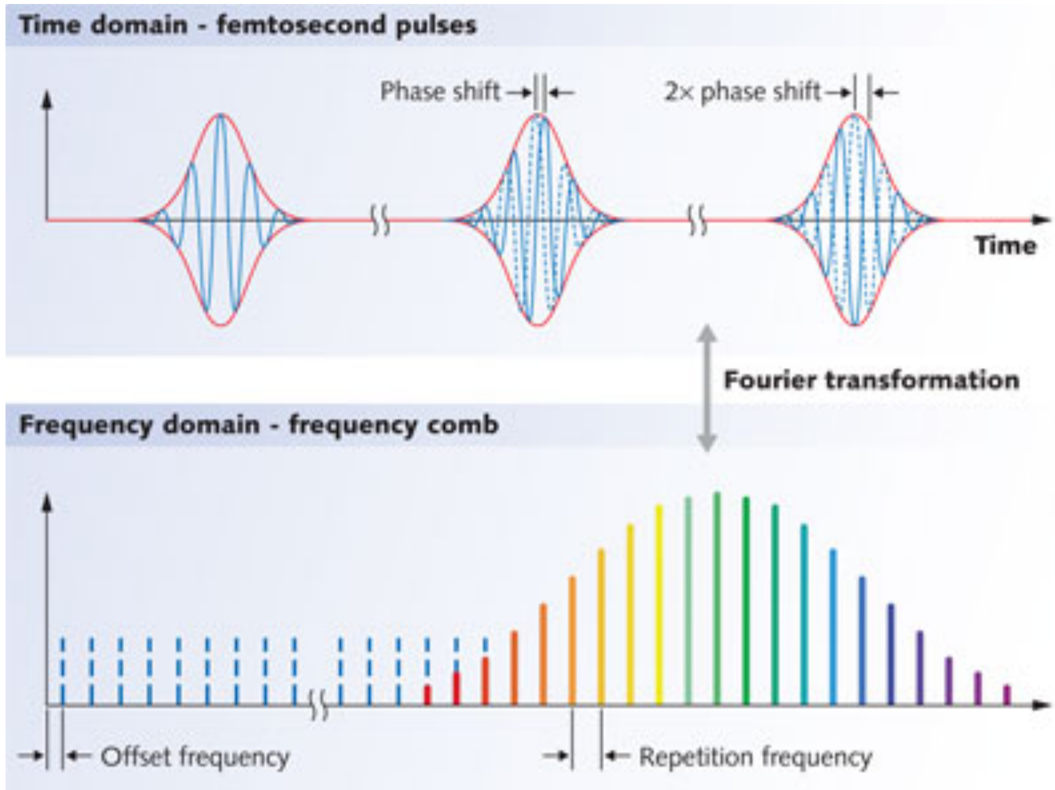


Many stable lasers simultaneously – well characterized



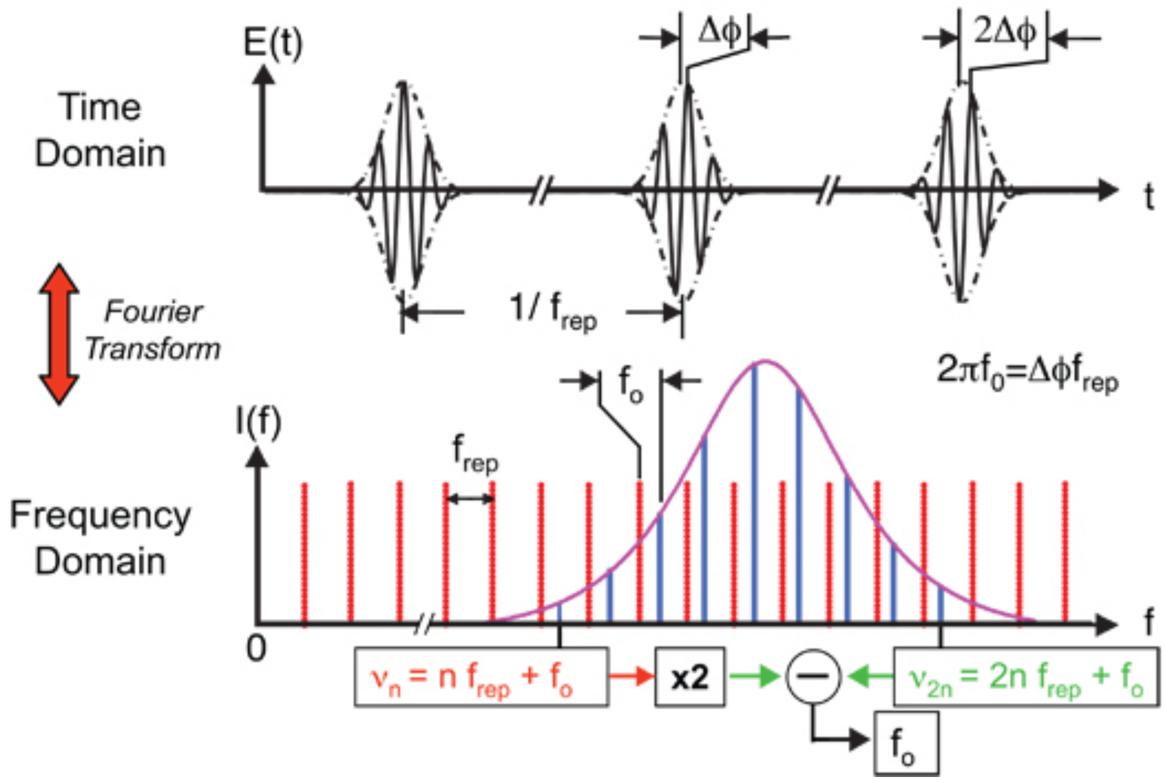


Optical Frequency Comb



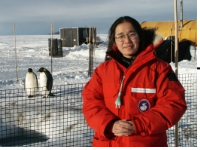
A frequency comb (bottom) is the Fourier transform of a train of mode-locked pulses (top). The frequency spacing of the teeth of the comb equals the pulse repetition rate. The spectral bandwidth of the pulse train, which can be enhanced by nonlinear effects, determines the frequency range of the comb. The comb frequencies are an integral multiple of the comb separation, plus an offset frequency, as shown at bottom.

Optical Frequency Comb



Optical frequency comb and characterization is an AMO physics breakthrough that led to Nobel Prize in Physics awarded to John Hall and T. W. Hänsch.

Frequency comb has found very wide applications, including laser radar!



Frequency Comb Lidar

- Compared to the filament white-light lidar, the frequency comb lidar employs millions of stable lasers at once. Such coherent light source can be better characterized and controlled, so it is very likely to result in well quantified and calibrated measurements of multiple species. Furthermore, I believe more sophisticated applications with the frequency comb lidars will emerge in the near future once people begin to look into this new field and make investment.

- Challenges occurring to me right now:

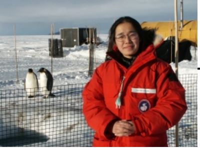
1) How to handle the frequency comb signals in the time domain? Tens MHz repetition rate and femto-second pulse width?

2) How to generate sufficient signals from the atmosphere of interest? If a retro-reflector is used, how to achieve range-resolved measurements?

3) How to detect the multiple species from the detector side?

4) How to deal with interference among multiple species ? …

- To my opinion, the frequency-comb-based white-light lidar or frequency comb lidar has a better future than the filament-based white-light lidar. Well-known laser sources always have superior advantages over incoherent or less-known light sources. How to apply frequency comb technologies to lidar is an intriguing question to lidar field.



What's New and What's Happening?

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

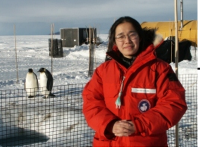
- External cavity diode laser (ECDL), Distributed Feedback (DFB) laser, Distributed Bragg Reflector (DBR) laser, Quantum-well or dot laser, Waveguide external cavity semiconductor laser (WECSL), etc.
- Diode-pumped Nd:YAG laser, Alexandrite laser, Fiber laser, Raman laser, …
- Optical parametric oscillator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

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

❑ Development of new spectroscopy principles and technologies, laser frequency control, and discovery of new species or species in unexpected regions, may enable new lidar technology and science applications.

❑ 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 160 km or higher. More lidars will be spaceborne in the future, including resonance-fluorescence Doppler lidar, etc.



Future Potentials and Growing Points

❑ Lidar remote sensing is an advanced technology, 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 the 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

(7) Laser break-down spectroscopy for composition measurements ?

❑ 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.