Research activities

1 Overview

Diels'group has been and/or is still engaged in collaborations with various groups around the world including the ACMS, a mathematics center at the University of Arizona, Tucson, the Czech Technical University, the CICESE center in Ensenada, Mexico, the ENSTA in Palaiseau, France, ICFO, Barcelona, Spain, the University of Geneva, Switzerland, and the School of Engineering of Glasgow University.

Dr. Diels has advised over 60 PhD and Master students. This meant not only providing financial support, but also as many original experimental projects and equipment. It also means maintaining and furnishing 7 optics laboratories. The 24 patents that have been awarded are a testimony to the diversity of this group's research. Over the last 10 years, to support these students and their projects, 8 M$ of research contracts and grants have been awarded, or an average of 800 k$ per year.

The research had a broader impact beyond just the circle of specialized peers. Dye laser pulses of 60 fs duration were widely advertised in the early 80's as the "world's shortest pulses". The lightning research has been featured often on the discovery channel, the history channel, and was the subject of an article in Scientific American. A book intended for the general public was prepared for the 50th Anniversary of the Laser. "The Power and Precision of Light" [1], written in collaboration with Ladan Arissian, is a book about lasers, how they are made, their applications and impact on our daily lives.

The 60 students that graduated over these years have moved to successful careers in industry National Laboratories and Universities. Some have made headlines for their research in the press (Scott Diddams in "the Times" and other newspapers for his work on Atomic Clocks, which he started in Diels' group, Jens Biegert of ICFO for his work on attosecond phenomena and high power ultrashort mid and long infrared sources, Jason Jones for his work on frequency comb cavity enhanced spectroscopy, Ladan Arissian for her work on electron momentum after tunnel ionization, and intracavity phase interferometry). Several students were awarded prizes for their dissertation work. These include:

- Jens Biegert, OSA fellow, awarded the 2004 Robert Allen prize from the Optical Society of America for work on coherent two-photon excitation of sodium. The citation reads: for "Exceptional interdisciplinary contribution combining the fields of coherent interactions and adaptive optics, leading to multiple wavelength guidestars."
- Xin Miao Zhao, 1994 Popejoy prize and Physics Department prize for her thesis on "Femtosecond ultraviolet pulse triggering of ground to cloud lightning"
- Ladan Arissian, 2007 Physics Department prize for best thesis on "Dark line resonance in 87Rb due to coherent interaction with mode-locked lasers"
- Patrick Rambo, 2000 Physics Department prize for best thesis on "Laser guided discharges"
- Scott Diddams (OSA fellow) and Briggs Atherton, Optical Science prize for best dissertation work 1997.
- Chengyong Feng, Optical Science prize for best dissertation work 2016, Marie Curie fellowship (to work in Italy with Prof Nisoli), and the 2015 Chinese Government Award for Outstanding Students Abroad.

The research and teaching have led to a textbook written in collaboration with Wolfgang Rudolph. This book has sold out a few years ago, and is still a basic graduate course in many Universities. A third edition should be available in 2019.

2 Areas of research

2.1 Femtosecond laser pulse phenomena

2.1.1 Development of fs sources

Various types of ultrashort pulse laser sources (ring dye laser, antiresonant ring, Ti:sapphire linear and ring, vanadate lasers, optical parametric oscillators) have emerged from Diels' group over the years. These studies continue with the dual purpose of understanding such sources (understanding the physics of ultrashort pulse formation) and providing tools for various experiments.

This group was one of the first to recognize the essential role of dispersion in femtosecond laser cavities, and to achieve intracavity pulse compression with prisms [2, 3], leading to 60 fs pulses, holding the world record in the early 80's.

2.1.2 Frequency combs, autostabilization

After an experimental demonstration that the modes of the mode-locked laser are equally spaced [4], we realized active (electronic) stabilization of frequency combs to a ULE reference cavity [5]. Further efforts thrived at moving away from electronic feedback loops. A theory of intracavity coherent interaction showed the possibility of *auto-stabilization* of a frequency comb [6]. Another method of autostabilization of an intracavity synchroneously pumped optical parametric oscillator was devised, based on opposite chirp of pump and signal [7]. Finally, purely optical coupling is substituted to the electronic loop to lock the modes of a frequency comb to those of a glass etalon [8].

2.1.3 Intracavity Phase Interferometry

Most researchers see the laser as a "black box" producing coherent radiation with which to perform some measurements. We have instead looked at the laser as the most sensitive sensor, if measurements are performed intracavity. In particular, we developed mode-locked lasers in which two ultrashort pulses circulate, to be used as active differential interferometers. The output of these lasers consists in two pulse trains of exactly the same repetition rate, but with a frequency difference proportional to the parameter being "sensed". This is the most sensitive phase sensor in the world, because a phase difference between the two intracavity pulses (caused by some external parameter being sensed) is converted directly into a frequency (the "beat frequency" measured by interfering the two pulse trains on a detector). A review of our work on Intracavity Phase Interferometry can be found in Photonics Review [9].

Inertial sensors (laser gyro without dead band with ring cavities; accelerometers in the case of linear cavities) are the most obvious applications. We have also demonstrated measurement of changes of index of refraction, linear and nonlinear, with a sensitivity better than 10^{-9} radians. The intracavity measurement has also been applied to the measurement of minute backscattering: an intensity backscattering coefficient of less than 10^{-15} can be resolved.

A new method has recently be devised to enhance the extraordinary phase sensitivity of intracavity phase interferometry by applying a giant dispersion to all modes of the comb [10]. This method is being tested in Ti:sapphire ring laser, and will be applied to fiber lasers.

2.1.4 Ultrashort pulse measurements in amplitude and phase

Numerous diagnostic methods to analyze the amplitude and phase of the ultrashort pulses have been pioneered, starting with the "interferometric autocorrelation" widely used since its first report in 1980 [11, 12]. The next generation was the "femtonitpicker" [13], multiple and single shot [14]; a forerunner to "Picasso" and "Mosaic", and most recently the pulse Characterization by Cascading Nonlinearity Inside a Spectrometer (CaNIS), involving simply a spectrometer and two nonlinear crystals.

2.2 Picosecond pulse generation and compression

2.2.1 Pulse compression by Stimulated Brillouin scattering

Methods of pulse stretching and compression are easily implemented with fs pulses using chirped mirrors, prisms and gratings. Chirped pulse amplification is used to reach PW peak powers in fs pulses. There is however a need for methods to generate and amplify pulses in the picosecond to nanosecond range. One method that we developed is to compress and amplify pulses by stimulated Brillouin scattering, leading to 170 ps pulses at 266 nm of 300 mJ [15, 16].

2.2.2 Pulse compression, bandwidth broadening by harmonic generation

In a new new physics involving saturated harmonic up-and down conversion, a field sometimes referred to as "nonlinear-nonlinear optics", a factor 60 compression was achieved through second harmonic generation in long crystals [17, 7]. More generally, the giant dispersion associated with the narrow phase matching bandwidth of long crystals can be exploited for large pulse bandwidth broadening and temporal compression [7]. This technique is being applied to the construction of a picosecond source at 355 nm, with adjustable chirp for the remote initiation of filaments.

2.3 Laser filamentation

We have pioneered the field of filamentation in air, starting in 1995 when we reported the first observation of UV filaments with femtosecond pulses [18]. Both UV and IR filaments are created in our laboratory out of a beam waist, prepared in vacuum and launched into the atmosphere through an aerodynamic window. This unique initial condition contrasts with all other studies, where the filaments are let to evolve from a macroscopic beam (several cm in diameter). In our vacuum-focused geometry, the Rayleigh range of the initial beam is only 8.5 cm. Therefore, the observed filamentation can only be associated with a true "light bullet", in contrast to the "moving focus" (a macroscopic beam self-focused at a distance decreasing with increasing intensity as observed in solids in the 70's) or nonlinear axicon focusing [19]. Furthermore, it has been shown that the nonlinear reshaping takes place before Fraunhofer diffraction. Beams with super Gaussian profile create for this reason a ring of multiple filaments when focused in air. If focused in vacuum, the focus profile is a Fourier transform of a square profile, thus with a parabolic profile in the middle, which, when launched in air, will create a single filament.

New research efforts are aimed at extending the range of filaments by creating nested filaments of different wavelengths, and high repetition rate filaments to establish a stationary waveguide in air.

2.3.1 Laser Induced Discharges and Lightning

We had demonstrated laser guiding across 30 cm gaps in air, at less than 1/4 the self-breakdown voltage, with ultrashort UV laser pulses of less than 20 mJ energy [20, 21]. We are investigating a scaling up of these experiment across larger gaps. Latest progress are reported in reference [22].

Key to successful long gap discharge are the use of multiple wavelength and long pulses to extend the lifetime of the generated plasma.

2.3.2 Remote high resolution spectroscopy

We have demonstrated better than 10 pm spectral resolution in remote spectroscopy of plumes generated by UV filaments on solid targets [23]. A new type of spectrometer for remote sensing is being developed. The Sagnac Fourier Spectrometer (SAFOS) combines compactness, high resolution and large input aperture [24].

2.4 References

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3 Patents

- “Efficient Particle Excitation for Isotope Separation” (4,188,538)
- “Laser gyro with a phase conjugating coupling element” (4,525,843)
- “Solid state laser gyro with interferometrically substracted noise” (5,191,390)
- “Mode-locked active gyro solid state lasers” (5,363,192)
- “Broadband, electronic femtosecond pulse measuring device” (application ref. UNM-424)
- “Discharge of lightning with ultrashort laser pulses” (5,175,664)
- “Apparatus and method for enabling the creation of multiple extended conduction paths in the atmosphere” (5,726,855)
- “Motion induced elimination of dead band in a short pulse laser gyro” (5,367,528)
- “Resonant cavity dither with index of refraction modulation” (5,251,230)
- “Biplanar cube unidirectional ring laser gyroscope” (5,650,850)
- “Ultra High Speed Line of Sight Laser Communications” (6,175,437 B1)
- “Sensors of rotation, displacement, index of refraction, magnetic field, electric field and magnetic susceptibility”; bidirectional short pulse ring laser (6,650,682)
- “Automatic Optical Fourier Mouré Wavefront Sensor” (6717661)
- “Gregorian Optical System with Nonlinear Optical Technology for protection against Intense Optical Transients” (7,236,297)
- “Ring laser scatterometer” (6,912,051)
- “Auto-Stabilization of Lasers By Means of Resonant Structures”, Ladan Arissian and Jean-Claude Diels (7,664,149)
- “Method and apparatus for femtosecond communication”, Jean-Claude Diels (7,593,643)
- “Radio frequency self-regenerative locked optical oscillator”, (8,379,285)
- ”Optical Scanning Nanoscope” Ladan Arissian and Jean-Claude Diels (8,446,592)
- “Frequency Comb of Large Spacing for Astronomy” Ladan Arissian and Jean-Claude Diels (8,488,639)
- “Multi Comb Generation with Fabry-Perot Etalon in a Mode Locked Laser for Intracavity Pulse Shaping and Fine Tuning of Wavelength and Repetition Rate” Ladan Arissian and J.-C. Diels (8,929,408).
- “Nested Frequency Comb for Absolute Index Measurement” (9,653,877).
- ”Intracavity fiber sensor” J.-C. Diels and Ladan Arissian (9,726,472)
- “Nested frequency comb” J.-C. Diels and Ladan Arissian (9,859,677)
- “Enhancement of the phase response of intracavity phase interferometers” J.-C. Diels and Ladan Arissian (provisional).