Ted Haensch – Sharing His Unique Perspective on Lasers

A talk on scientific lasers with the Nobel laureate

Someone with a history in the field of lasers nearly as long as that of the laser itself is Theodor "Ted" Haensch, who was awarded the 2005 Nobel Prize in Physics for his work in precision spectroscopy and in developing highly stabilized frequency combs. In various capacities within Coherent, Peter Vogt has been privileged to know Professor Haensch for 25 years and had the opportunity to interview him about his unique experience in lasers and laser spectroscopy.

Fig. 1 Nobel Prize winner Ted Haensch (r.) gives insight in his nearly-50 year perspective on scientific lasers in this interview with Peter Vogt (l.).

O&P: Long before your work with stabilized frequency combs you were well-known to many in the laser community because of your work stabilizing nanosecond dye lasers at Stanford – "The Haensch-type dye laser".

TH: After I finished my PhD at Heidelberg, where I had studied nonlinear effects in high resolution spectroscopy with helium neon lasers, I secured a NATO post-doc position with Professor Art Schawlow at Stanford University. Fortunately, I had witnessed a dye laser being pumped by a commercial nitrogen laser when I visited Bell Labs on my way to California. I persuaded Art that we should acquire a nitrogen laser, and that I would attempt to build a widely tunable dye laser with narrow linewidth for performing Doppler-free saturation spectroscopy experiments. The problem with the dye laser at that time was linewidth and wavelength control; the intracavity beam only impacted a small area of the diffraction grating that acted as a wavelength filter. I often carried a small monocular (telescope) for visualizing distant objects, and it occurred to me to use this to expand the beam over a much larger area of the grating. I also inserted a Fabry-Pérot etalon in front of the grating, and the rest is history. This laser type enabled laboratories around the world to study Doppler-free saturation spectroscopy, two-photon spectroscopy, coherent Raman processes, and Rydberg states, among others. Our own work included spectroscopy of the Balmer-alpha line in hydrogen at high resolution, which was cited as part of the work ultimately leading to Art Schawlow being awarded the Nobel Prize in Physics in 1981. Lambda Physik in Göttingen was one of the first companies to commercialize the "Haensch-type" dye laser. It became part of Coherent in 2003.

O&P: To me, your work with the nanosecond dye laser is a perfect example that encapsulates much of your prestigious career; first, improving existing laser technology to provide a new tool, and then using that tool to probe physics with previously unattainable resolution and sensitivity.

TH: Thank you. Since I was a boy, I always wanted to work on the frontier of science. Also, I must confess to prefer working in a fairly unstructured, free-thinking way. As an undergraduate I realized that research at some frontiers, such as particle physics, required massive collective effort and investment which did not suit my personality and interests. But, I quickly realized that with lasers, I could explore a different frontier: I could look where no one had looked before. By pushing atomic and molecular spectroscopic measurements to new limits of resolution and precision, I hoped to find unexpected deviations from theory and perhaps ultimately discover new physics beyond the Standard Model.

My early days at Stanford included my first association with Coherent, which was then a very young company based near the University. When I was appointed to a faculty position, I started out with an argon ion laser. Over the next decade and half, I acquired several Coherent cw lasers, including the 699 and 899 ring dye lasers.

O&P: Your work with control and cavity locking using our cw ring dye lasers ended up leading to new commercial products that once again enabled you and other scientists to push the experimental envelope. For instance, we ended up developing a 266 nm cw laser called Azure using a resonant build-up cavity based on the "Haensch-Couillaud" locking technique to frequency double the output of a 532 nm DPSS vanadate laser.

TH: Yes, Bernard Couillaud was a visiting scientist at our laboratory at Stanford, on leave from the University of Bordeaux, when we first demonstrated this new locking technique. He later became CEO at Coherent. We were able to lock a cw ring laser to a stable passive cavity with a linewidth of a few kHz.

We used that locking technique to stabilize a build-up cavity to frequency double 486 nm visible light to 243 nm in the UV, which enabled us to observe the sharp 1S-2S two-photon transition in atomic hydrogen with kHz resolution. At the time that was ground-breaking, but of course kHz linewidths today are almost trivial. Just look at the LIGO system that recently measured gravitational waves for the first time. The LIGO team is locking the frequency of your monolithic Mephisto lasers to sub-Hz linewidths and stability.

But that's part of the attraction and magic of laser science for me. A cutting edge innovation soon goes from a laboratory demonstration to become a tool for wider scientific use. But, that tool eventually gets superseded by something newer and better, and so it goes on.

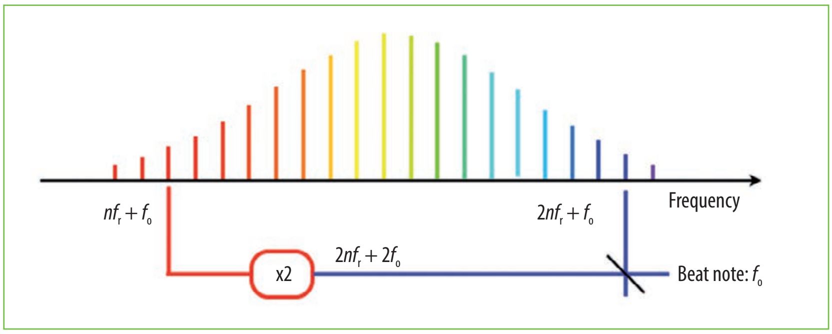

Fig. 2 Working principle of the carrier envelope phase (CEP) stabilization

O&P: In the interests of brevity, I realize I'm skipping over many years of your successful career in cutting edge science, but let's talk about your most famous innovation. The femtosecond frequency comb won you the 2005 Nobel and is already a widely used tool in some diverse applications.

TH: Well, the concept came to fruition in the late 1990s, about ten years after I returned to my native Germany to create and direct a laser spectroscopy division at the new Max Planck Institute of Quantum Optics in Garching in 1986. But the story of frequency combs actually started back in my Stanford days with Jim Eckstein, who was one of many talented PhD students that I have been fortunate enough to work with. In the mid-seventies, Jim and I worked on frequency combs from both picosecond and femtosecond dye lasers – this was in the days before the titanium:sapphire solid state revolution in ultrafast optics. We had identified that the dispersion inside the laser resonator would lead to unknown phase slips of the carrier-wave relative to the pulse envelope and therefore with a comb spectrum spanning only 800 GHz, we had no means to observe and measure the offset frequency and to know the absolute positions of our comb lines. But they could already serve as a frequency ruler to measure some atomic fine structure intervals.

Actually, a key breakthrough moment for me was when I visited your display booth at a conference. You had a Mira oscillator seeding a femtosecond amplifier and that was focused into a disk of sapphire to generate a white light continuum. I noticed that this white light exhibited speckle and was hence spatially coherent. I was hoping that the process might be fully coherent while covering a huge range of the electromagnetic spectrum. In early 1997, I worked with Marco Bellini in Florence, Italy, where we could demonstrate interference of white light pulses. Then everything came together fairly rapidly. At the end of the 1990s, my group first used the frequency comb structure of a femtosecond mode-locked titanium:sapphire laser to bridge large frequency intervals in a simplified frequency chain linking optical and microwave frequencies. Lucent Technologies demonstrated the ability to efficiently generate a white light continuum with hollow core fibers, initially called "holey fibers," but now often called photonic crystal fibers. Our group was then in a bit of a race with the team of John Hall in Boulder to get our hands on this type of fiber in order to generate these massively extended frequency combs. We finally obtained a similar fiber from the group of Philip Russel, then at the University of Bath, England, and within days we realized our first self-referenced octave-spanning frequency comb synthesizer. At the same time, the Boulder team achieved similar success after obtaining the fiber from Lucent Technologies.

Today, such broad combs provide a continuous connection of frequencies from the microwave region to the UV. In the 1990s, we spent years perfecting tools such as coherent frequency interval dividers so that we were able to verify the precisely even spacing of the comb lines from a mode-locked titanium:sapphire laser. We were the first to lock such a frequency comb to a commercial cesium clock in our laboratory, so that we could give *absolute* calibration to optical spectroscopy with unprecedented precision. For example, in June 1999, we were able to measure the 1S-2S hydrogen atom absorption frequency to 14 decimal places by referencing it to a transportable cesium fountain clock built at BNM SYRTE in Paris.

Fig. 3 Ted Haensch showing a current optical setup in his Garching lab.

O&P: The frequency comb also gave laser manufacturers and laser users a way to control the electric field – carrier envelope phase (CEP) stabilization – enabling a route to attosecond physics among other things.

TH: Yes. Once we had a coherent comb spanning an octave, it became easy to demonstrate f-$2f$ phase locking. My sketch (see Fig. 2) schematically shows how this works: The spacing between adjacent comb lines is always precisely equal to the pulse repetition frequency. However, the phase of the carrier wave relative to the pulse envelope (CEP phase) is generally slipping from pulse to pulse, so that all comb lines are shifted by the so-called carrier-envelope offset frequency. To measure this offset frequency, we take light from the red part of the comb spectrum and send it through a nonlinear doubling crystal which produces new comb lines near the blue part of the comb, now shifted by twice the offset frequency. A collective beat note with the original comb lines directly gives the offset frequency and can be used for CEP stabilization. In fairness, I must note that other routes to measure and stabilize the phase offset have been developed too.

O&P: Can you give the readers a quick overview of the types of scientific measurement these developments have enabled.

TH: Well you already mentioned attosecond physics so let's start there. CEP stabilization makes it possible to generate ultra-short laser pulses with reproducible wave form of the electric field, down to pulse lengths of just a single optical cycle. Ferenc Krausz and others have done amazing work generating high harmonics in the deep UV and X-ray regions, with a spectral bandwidth enabling compression to the attosecond regime. As a spectroscopist myself, I was very excited when they showed that these pulses could be used to directly observe the behavior of inner electrons in the time domain. This crossed an important frontier in the study of molecular physics. During the entire history of electronic spectroscopy before that, the behavior of electrons was always inferred from the motion of nuclei via the Born-Oppenheimer separation.

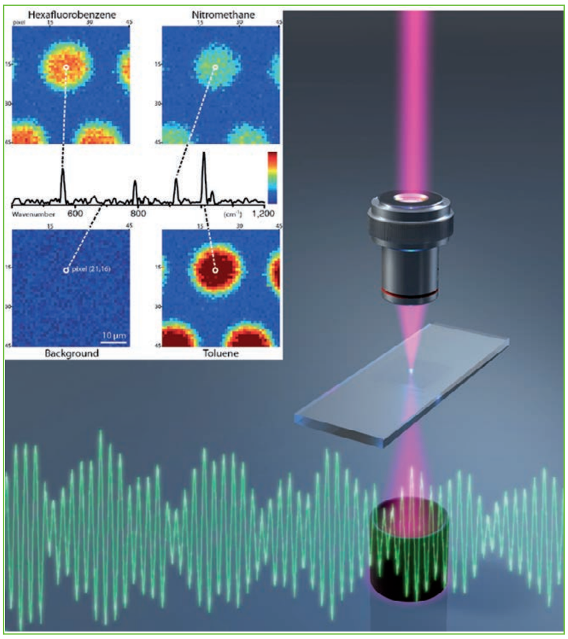

Fig. 4 Investigation of how two synchronized frequency combs can provide novel opportunities in label-free spectral imaging of biosamples.

The frequency comb concept itself has lots of applications. For example, it has enabled optical clocks with one hundred times the precision and accuracy of microwave clocks. The ability to increase temporal resolution by two orders of magnitude will surely reveal some interesting and unexpected wrinkles in several areas of physics. The comb is also used to produce ultrastable microwaves. Frequency combs will lead to advances in satellite navigation systems, telecommunication links, and radar. Astronomers are using frequency combs to search for earthlike extra-solar planets by looking at tiny Doppler shifts of stellar spectral lines due to the wobble in the radial velocity caused by an orbiting planet. It may also become possible to directly observe the accelerating expansion of space in our universe. Specifically, astronomers can look at the absorption spectra of intergalactic hydrogen gas clouds in the light of distant quasars now and again in twenty years on the same absolute scale to see if / how it has changed.

Frequency combs are also in the early stages of revolutionizing Fourier transform spectroscopy from the vacuum ultraviolet to the infrared and even longer wavelengths such as the THz region. Nathalie Picqué has been the first to show that the sensitivity of a Fourier spectrometer can be greatly increased if a laser frequency comb is used instead of an incoherent light source. Even more dramatic advances in sensitivity and recording speed become possible, if two frequency combs of slightly different pulse repetition frequencies are used. A single fast photodetector reveals radio frequency beat notes between corresponding lines from each comb, and there is no need for any moving parts. To achieve similar recording speed with the Michelson approach would need a mirror moving at the earth escape velocity!

O&P: Can you take a little time to talk about particular experiments and applications you yourself are currently working on.

TH: Well, as you know, in my personal lab I have a couple of your compact Vitara femtosecond lasers. I'm working with Nathalie Picqué and other colleagues to investigate how two synchronized frequency combs can provide novel opportunities in label-free spectral imaging of biosamples, in particular four-wave mixing techniques of the coherent anti-Stokes Raman-scattering (CARS) type. This illustration (Fig. 4) gives an artist view of our approach, together with an experimental hyperspectral image. Such an approach can simultaneously measure, on the microsecond timescale, all spectral elements over a wide bandwidth and with high resolution on a single photodetector. We therefore expect that our approach of using laser frequency combs will not only enable new applications for nonlinear microscopy, but also benefit other nonlinear spectroscopic techniques.

O&P: And looking into the future?

TH: Making long term predictions about the future is always a risky business. In terms of applications of frequency combs and supercontinuums from femtosecond lasers, I think we really are at the early stages of application development. In terms of lasers, we'd all like to see the ideal tunable laser source. This would be a widely tunable source, probably an OPO, where you could type in the wavelength you want and get it instantly. Taking an even higher altitude view, it seems to me that solid state lasers will carry on their current trajectory of becoming increasingly smaller packages with ever more powerful output and an expanding range of wavelengths. In turn with this will make possible an even broader range of scientific investigation.

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The interview was conducted and provided by Dr. Peter Vogt, Director of Field Sales Europe, Coherent, and Petra Wallenta, PR / Marketing / Communications Manager Europe, Coherent GmbH, Dieburg, Germany.

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