MODE-LOCKED LASERS

Light condensation

Common sense suggests that complex phenomena such as Bose–Einstein condensation require complicated experimental set-ups to be observed. But when it comes to the field of photonics, the simplest system may sometimes reveal the most unexpected surprises.

Andrea Fratalocchi

In 1924, Albert Einstein extended the mathematics of the Indian physicist Satyendra Nath Bose to cover an ensemble of non-interacting atoms. In doing so he created what is now famously known as Bose–Einstein statistics, a model that describes the population distribution of non-interacting atoms over their energy states in thermal equilibrium. Einstein used this model to predict the existence of a peculiar state of matter in which "a separation is effected: one part condenses [into its lowest energy state], the rest remains a 'saturated ideal gas'"[1]. This ultimately led to one of the most important discoveries of the twentieth century: the phenomenon known as Bose–Einstein condensation[2]. Experimental demonstration was initially difficult because of the ultralow temperatures required, but was finally achieved by Eric Cornell and Carl Wiemann in 1995 at the University of Colorado — a success for which they were awarded the Nobel Prize for Physics in 2001.

In recent years the search for similar condensation phenomena in the field of photonics has generated much interest[3,4], with such condensation effects being both theoretically predicted and experimented reported in random resonators (random lasers)[4]. Now, Rafi Weill, Baruch Fischer and Omri Gat have theoretically suggested the occurrence of light condensation in a laser system far simpler than that of a random resonator — namely an actively mode-locked laser[5], which has the great advantage of being easily controllable in experiments. By applying a statistical theory to describe the interaction of many incoherent laser modes in the presence of active mode-locking — a well-known technique for producing ultrashort pulses[6] — Weill and colleagues were able to map the laser dynamics onto an equivalent Bose–Einstein condensate, thereby creating a system that undergoes condensation when the overall laser power inside the cavity increases beyond a threshold value. The observable optical manifestation of this effect takes place in the spectrum of excited modes; these shrink in size and thus drive the overall lasing process towards single-mode emission (Fig. 1).

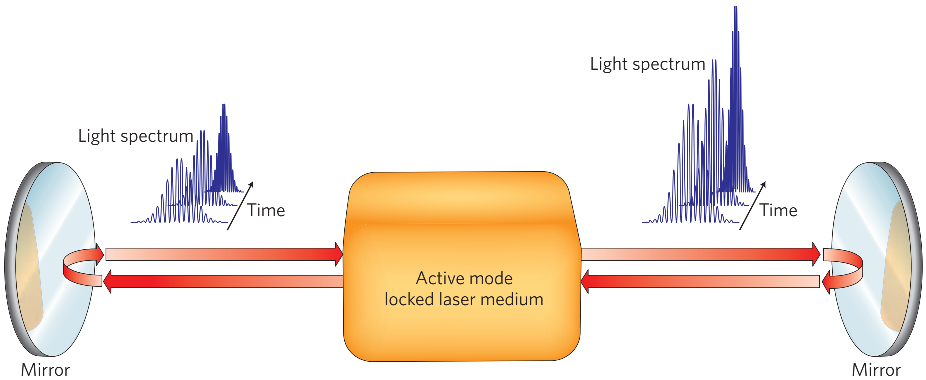

Figure 1 | The proposed set-up for observing light condensation. A suitable active mode-locked laser amplifies and modulates an incoherent spectrum composed of many laser modes in time. As soon as the overall light power in the cavity exceeds a certain threshold, a condensation process is expected to occur: at every round trip each mode transfers a fraction of its power to a single mode, thus shrinking the overall spectrum, condensing light energy and resulting in single-mode lasing.

The key idea of Weill and co-workers is the use of unconventional schemes for the active mode-locking. Standard active mode-locking is usually implemented by acousto-optic modulators, which, being driven by sinusoidal waveforms, generate harmonic modulations of light amplitude inside the laser cavity. The existence of such harmonic functions in the presence of many incoherent laser modes allows even low-amplitude noise to destabilize the dynamics, thus prohibiting any constructive mode interaction. However, by assuming periodic modulation characterized in time by specific non-smooth behaviour (the authors here investigated a power law dependence), the mode interaction dramatically changes and a 'cooperation' settles in; in this condition, during each round trip into the laser cavity, every mode coherently transfers a fraction of its energy into a single mode of the ensemble, thus gradually increasing the energy of this single mode over time.

An attractive feature of the build-up process lies in the possibility of generating laser pulses with energies higher than those created through conventional active mode-locking, in which the basic mode carries only a small fraction of the total cavity power. Another important direct consequence of light condensation is a sharp rise in the coherence time of the emitted laser pulse. By delivering laser energy into a single mode, the condensation process is able to shorten the coherence time by a factor that is proportional to the initial number of oscillating modes into the cavity.

Although the insights provided by Weill *et al.* are likely to be relevant to many different laser systems, certain limitations of their analysis should be mentioned. In particular, their theoretical model does not currently take into account overlapping modes, which result from the damping and noise inflicted by the external radiation field[7]. The inclusion of this contribution increases the laser linewidth with respect to that predicted by the Schawlow–Townes law[7], and this overlapping effect may counteract light condensation. An important next step would therefore be to investigate this process and its implications to the theoretical predictions of Weill *et al.*

Aside from such issues, the predictions of Weill *et al.*[5] will certainly have significant implications in the field for stimulating new ideas, both in the design of new ultrashort coherent lasers and in the comprehension of complex dynamics of light organization in systems characterized by many degrees of freedom. ❐

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References

1. http://nobelprize.org/nobel_prizes/physics/laureates/2001/cornellwieman-lecture.pdf
2. Ketterle, W. *Rev. Mod. Phys.* **74,** 1131–1151 (2002).
3. Connaughton, C. *et al. Phys. Rev. Lett.* **95,** 263901 (2005).
4. Conti, C. *et al. Phys. Rev. Lett.* **101,** 143901 (2008).
5. Weill, R., Fischer, B. & Gat, O. *Phys. Rev. Lett.* **104,** 173901 (2010).
6. Brabec, T. & Krausz, F. *Rev. Mod. Phys.* **72,** 545–591 (2000).
7. Hackenbroich, G., Viviescas, C. & Haake, F. *Phys. Rev. Lett.* **89,** 083902 (2002).

TERAHERTZ TECHNOLOGY

Towards THz integrated photonics

The demonstration of an integrated terahertz transceiver featuring a quantum cascade laser and a Schottky diode mixer promises new applications for compact and convenient terahertz photonic instrumentation.

Heinz-Wilhelm Hübers

The terahertz (THz) spectral range, located between the infrared and millimetre-wavelength spectral regions, is one of the least-explored parts of the electromagnetic spectrum. Although it has interesting applications in astronomy, particularly for spaceborne THz-sensing observatories such as the Herschel Space Observatory[1], the THz range still remains a rather exotic field. In the past few years there has been increasing attention on THz research and development, triggered by tremendous progress in the development of sources, detectors, optics and systems. THz technology is now on the verge of seeing commercial applications, for example in security, biomedicine, broadband communication, non-destructive testing and process control[2].

An important technique in THz research, particularly for 'real-world' applications, is heterodyne detection. Widely used in radiofrequency telecommunications, heterodyne detection is popular because of its sensitivity, narrow bandwidth and ability to measure high-frequency signals, for which direct detection would otherwise prove challenging. The principle of heterodyne detection is that a signal carrying information is combined with radiation from a local oscillator operating at a frequency near that of the signal (Fig. 1a) using a component called a 'mixer'. The output from the mixer is a new signal that oscillates at a frequency called the beat frequency, which is equal to the frequency difference between the local oscillator and the original signal. The beat frequency is often easier to amplify and process than the original signal because it is at a much lower frequency.

In existing THz heterodyne receivers, the local oscillator and mixer are discrete units, making the whole system rather complex and thus limiting applications mostly to fields such as astronomy or Earth observation. Much current research focuses on developing discrete heterodyne receivers with quantum-noise-limited performance, which requires superconducting mixers to be cooled to around 4 K. For cases in which cooling to such low temperatures is not an option, Schottky diode mixers can be used instead, but at the expense of lower sensitivity. In addition, heterodyne arrays with modest (less than 20) pixel numbers have also been realized, or are at least currently under development. However, all of these approaches rely on discrete mixer and local oscillator units. The realization of integrated circuits for performing various THz signal processing tasks is therefore highly desirable as it could ultimately allow the production of convenient, compact and potentially mass-producible low-cost equipment for THz applications.

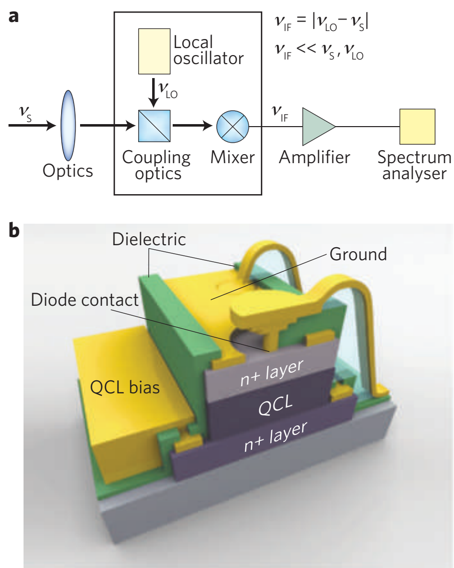

Figure 1 | Scheme of a heterodyne receiver and an integrated transceiver. **a**, The principle of operation of a heterodyne receiver. ν_{LO} is the frequency of the local oscillator, ν_S is the frequency of the signal and ν_{IF} is the beat frequency generated by the mixer. ν_{IF}, the difference between ν_{LO} and ν_S, is often easier to amplify and process than ν_S because it is at a much lower frequency. **b**, Structure of the integrated transceiver of Wanke *et al.* The Schottky diode is on top of the QCL waveguide ridge. The integrated transceiver replaces the discrete local oscillator and mixer units as well as the coupling optics shown in **a**.

Now, writing in *Nature Photonics*, Michael Wanke and co-workers from Sandia National Laboratories and LMATA Government Services in the USA report the first step towards this goal, with the demonstration of integrated circuitry for performing THz heterodyne detection[3]. The researchers have successfully demonstrated an integrated THz transceiver consisting of a 2.8 THz quantum cascade laser (QCL) as a local oscillator and a Schottky barrier diode as a mixer. They show that this integrated circuit performs basic but important functions such as the transmission of a coherent carrier, heterodyne detection of an external signal, and frequency locking and tuning.

THz QCLs are typically based on a thin (~10 μm) GaAs/AlGaAs superlattice on a semi-insulating GaAs substrate[4]. The superlattice is the active medium of the laser and has the form of a ridge a few millimetres long and 50–200 μm wide. On top of the ridge is a metal layer, and between the ridge and the substrate another metal layer or a highly doped GaAs layer is located. These layers form the waveguide of the QCL. The laser drive current is supplied through the