Photonics

Electrons turn wire into a laser-like light source

Nicholas Rivera

Shining a laser on an iron wire generates fast-moving electrons that boost the electromagnetic waves created by the light interacting with the wire. This way of making laser-like light could surpass existing methods that use electrons. See p.55

The laser is among the most far-reaching innovations of the twentieth century, and its impact shows no signs of diminishing. The light created by lasers is exceptionally bright, and its phase – the degree to which the light waves are in step with each other – remains stable over long distances. However, laser light is typically restricted to a very narrow range of wavelengths. This limitation prompted the development of a device known as the free-electron laser, which can (in principle) emit light at almost any wavelength. The problem is that free-electron lasers usually require high-power devices housed in large-scale facilities. Now, on page 55, Zhang *et al.*[1] report an approach to building a free-electron laser that might yet deliver a compact source of laser-like light.

Although the detailed physics of what goes on inside a laser is typically complex, all conventional lasers share a common basic operational principle: a process known as the stimulated emission of photons (electromagnetic radiation). Feeding energy into a material called a gain medium can have the effect of promoting the electrons in the medium to higher energy levels. Left to their own devices, electrons will often give up this new-found energy by emitting photons through a process called spontaneous emission. But emission of photons can also be 'stimulated' by irradiating the gain medium with photons of the same wavelength as those produced by spontaneous emission. The resulting electrons then emit light with exactly the same properties as the incoming light.

The rate at which these stimulated photons are produced is proportional to the number of photons present, which amplifies the total number of photons exponentially and leads to a bright beam with a well-defined direction and wavelength[2]. However, this wavelength is not easy to modify, because it is determined by the fixed energy levels of the electrons in the gain medium. For this reason, many kinds of gain medium are now available, each able to provide different wavelengths of laser operation.

The difficulties involved in tuning conventional lasers led to the invention of a fundamentally different type of laser, which is based on the emission of light by energetic electrons not bound to matter (free electrons). The kinetic energies of electrons are often much larger than are those of any photons they can emit, so light sources that use electrons can emit photons at essentially any wavelength in the electromagnetic spectrum: from radio frequencies, all the way down to X-ray wavelengths. The wavelength of the emitted light can be tuned by changing the electron velocity, which makes light emission by free electrons a suitable method for constructing versatile and tunable sources of light[3].

Similarly to the electrons in the atoms of the gain medium used in conventional lasers, a free electron can also have its emission stimulated by photons. If the electron passes through an electromagnetic field near the crest of the electromagnetic wave, it gets decelerated and gives up energy that is transferred to the field at the same wavelength, direction and polarization as those of the electromagnetic wave[4]. This results in the laser-like stimulated emission of photons.

Although the physical principle of stimulated emission by free electrons is simple, it is challenging to realize. The process requires efficient interaction between electrons and light, which imposes stringent requirements: for example, high-power electron beams with well-controlled velocities, and careful alignment of the electron beam with the sample supporting propagation of the electromagnetic wave. Demonstrations of the net stimulated emission have therefore been restricted almost exclusively to high-power devices operating at microwave frequencies[5] (10^9 hertz), with very few realizations at terahertz frequencies[6] (1 THz is 10^{12} Hz) and almost none at optical frequencies[7], which can reach hundreds of terahertz. Because stimulated emission by free electrons is so difficult to achieve, the way in which the electromagnetic field builds up is not well understood. This is especially true for 'ultrafast' processes, in which ultrashort pulses of electrons are used to rapidly generate a short pulse of electromagnetic energy (in a loose analogy to pulsed lasers).

Zhang *et. al.* addressed these difficulties by taking a different approach. Rather than producing an electron beam with an electron microscope, the authors used intense conventional lasers (Fig. 1). By irradiating the end of an iron wire with a powerful infrared pulse lasting only femtoseconds (1 fs is 10^{-15} s), they were able to generate a short pulse of electrons (30 fs in duration). The intense electric field created by the laser pulse effectively stripped the electrons from the iron atoms, accelerating them to a very high velocity (roughly 0.6 times the speed of light) and sending them rapidly down the wire.

The iron wire served not only as a source and a 'channel' for the electrons, but also as an optical medium supporting travelling electromagnetic waves. The electric field generated by the electron pulse made other, mobile, electrons in the iron wire oscillate, inducing spontaneous emissions that manifested in an

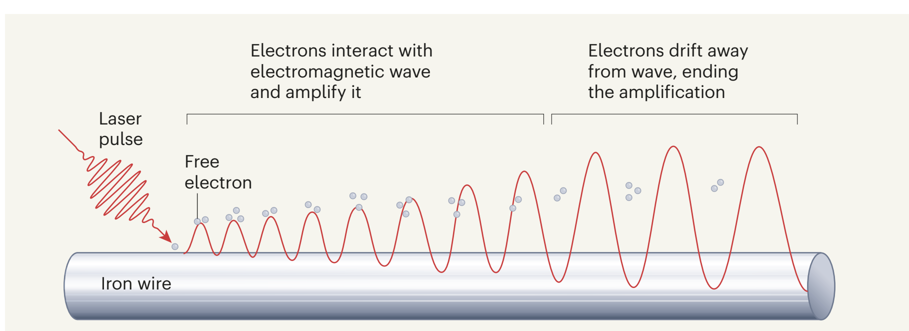

Figure 1 | Amplification of light by laser-induced free electrons. Zhang *et al.*[1] generated a short pulse of free electrons by irradiating the end of an iron wire with a powerful laser pulse that accelerated the electrons with high velocity down the wire. These electrons made other electrons (not shown) in the iron wire emit electromagnetic waves, with which the free-electron pulse then interacted. Because these interactions always occurred near the crest of the wave, the electrons transferred energy to the waves, amplifying them until the electrons drifted away and the amplification ceased. The effect could be used to make a compact version of a device, known as a free-electron laser, that can emit laser-like light with a broad range of wavelengths.

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electromagnetic wave propagating through the wire. The free electrons in the pulse then interacted with and amplified this wave. The short nature of the pulses and the properties of the iron medium ensured that the emissions always occurred near the crest of the electromagnetic wave, leading to a guaranteed transfer of energy from the electrons to the field until the electrons and the light drifted apart.

A crucial aspect of Zhang and colleagues' study is the detailed characterization of the build-up of light. By placing a terbium gallium garnet crystal in the vicinity of the iron wire, they were able to read out the magnetic field of the light as the waves were seeded and amplified. The electric field could be similarly determined using a zinc telluride crystal. The presence of an electromagnetic field modifies the optical properties of these crystals, which can be measured by a second laser beam. The authors' detailed spatio-temporal mapping of the field revealed that it built up over one millimetre of the iron wire, and within a few picoseconds (1 ps is 10^{-12} s). These results are consistent with the expected dynamics of a short electron pulse in a self-generated electromagnetic field.

Zhang and colleagues' innovative approach to free-electron stimulated emission could be extended by considering other media that support electromagnetic waves. The authors used a simple wire made of iron, with no geometrical structure in the direction of electron propagation. The effects reported here could be amplified and enhanced by structures whose electromagnetic properties vary in space (for example, artificial materials called photonic crystals or metamaterials)[8]. Such spatially structured materials can offer marked control over the behaviour of light – a capability that has been used extensively in the field of nanophotonics to shape the spontaneous and stimulated emission of visible and infrared light.

Another potential extension of this experimental set-up involves the amplification of radiation at optical (visible and infrared) frequencies, which are higher than those used by the authors. Ultrafast amplification of visible radiation would require subfemtosecond pulses of electrons, but these are already becoming available, owing to advances in our understanding of how electrons interact with strong laser fields[9]. The prospect of replicating Zhang and colleagues' findings with visible radiation is particularly exciting, because it could lead to highly compact sources of amplified light. This could be especially useful in materials, such as silicon, that are widespread and readily fabricated, but that have so far proved challenging to use as media for lasers.

Nicholas Rivera is in the Department of Physics, Harvard University, Cambridge, Massachusetts 02139, USA.
e-mail: nrivera@fas.harvard.edu

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Ecology

The point of no return for species facing heatwaves

Susana Clusella-Trullas

A climate-driven rise in exposure to extreme temperatures will hasten mortality. To predict such losses, we need to know how quickly organisms succumb to stressful temperatures. A study shows how heat-failure rates vary across species. **See p.93**

Heatwaves associated with climate warming are predicted to continue to increase in frequency and intensity this century[1]. These events have already caused catastrophic population declines and the reorganization of biological communities in certain places[2]. Understanding how quickly, and to what extent, temperature extremes will have consequences for organisms is pivotal to predicting the effects of future climate warming. On page 93, Jørgensen *et al.*[3] look at the rate at which biological functions vary with survivable changes in temperature and compare that with the rate at which death occurs at extreme (stressful) temperatures. Their analysis reveals that, at stressful temperatures, even a small temperature rise will quickly result in strikingly negative effects on the survival of organisms.

The authors' study focused on organisms called ectotherms. Creatures in this group, such as insects and reptiles, have only a limited ability to internally regulate their own temperatures. Ectotherm body temperatures are therefore tightly linked to environmental conditions, and their temperature tolerances largely predict their species distributions, especially for marine groups[4].

Using a large compilation of published data, Jørgensen and colleagues calculated the rate at which various biological traits respond to temperature across a wide range of organisms. However, unlike the approach taken in previous studies, Jørgensen *et al.* distinguished between the temperature sensitivity of traits in permissible temperature ranges and those in stressful temperature ranges (Fig. 1). The permissible range reflects temperatures that enable animal homeostasis and growth, despite potential detrimental effects relating to ageing and limited performance. Numerous and diverse sets of traits have been assessed in this permissible range, from biochemical pathways to aspects of whole-organism performance (such as movement rate, or cellular processes that produce the energy-carrying molecule ATP). By contrast, the stressful range encompasses temperatures that result in the imminent death of the organism owing to irreversible heat injury – known as heat failure.

Although mechanisms that underpin heat failure are less-well understood than are those underlying performance in the permissible range, many scientists have determined the

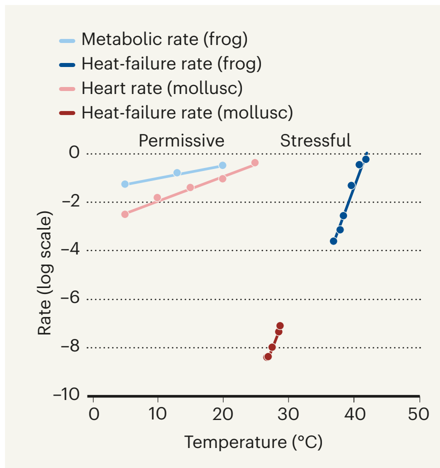

Figure 1 | High temperature has a severe effect on the rate of animal mortality. Jørgensen *et al.*[3] studied the effects of heatwaves due to climate change. The authors used published data to examine how changes in temperature affect the rate of biological processes at temperatures at which species function normally (permissive temperatures), and how they affect the rate of heat failure (irreversible changes leading to lethality) at stressful temperatures. Rising temperatures drive a rapid increase in heat-failure rates (as indicated by steep slopes in this graph). (Data taken from ref. 3.)

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