Photonics

# Low-power light modifies electron microscopy

Martin Kozák

An optical device designed to control the properties of electron waves inside an electron microscope demonstrates that clever platforms for integrated photonics need not be powered by expensive laser systems. **See p.653**

The wavelength of an electron can be up to 100,000 times shorter than that of a photon, which means that microscopes that use electrons to illuminate a sample are able to resolve much smaller structures than can those that use light. But electrons and photons also work together: interactions with photons can be used to modulate the wave-like nature of electrons, changing the energy spectrum of the electron beam in a way that could be useful for tailored microscopy[1]. However, these electron–photon interactions are weak, and usually require high-power laser sources. On page 653, Henke *et al.*[2] report an optical platform for manipulating the properties of electron waves using a light source that is not much more powerful than an average laser pointer. The low light power required of this device, together with its integrated design, make it readily applicable to many existing electron microscopes.

The idea of stimulating interactions between electrons and photons was considered during the early development of quantum mechanics, when physicists Pyotr Kapitza and Paul Dirac predicted that an electron beam would generate a diffraction pattern when passing through a periodic structure made of interfering light waves[3]. The prediction turned out to be correct, but it took many decades to prove, because the interaction occurs with very low probability, and demonstrating it requires experiments using high-power laser pulses[4].

Techniques for improving the efficiency of the coupling between light and electrons have since been introduced[5,6]. These methods manipulate light through its phase, the fraction of the waveform completed at a given point in time. The idea is to match the phase velocity — the velocity at which the wave oscillations propagate — to the velocity of the electrons, which then 'surf' the light wave. This, in turn, modulates the phase of the electron's wavefunction (which determines the probability that the electron will have a particular velocity and kinetic energy at a specific location) through its de Broglie wavelength, the length scale at which the wave-like properties of the electron emerge. The phase is changed every few femtoseconds (1 fs is $10^{-15}$ s), splitting the electron's energy spectrum into several values separated by the photon energy of the light wave.

However, even such efficient coupling must be strongly driven by high-power laser sources. Other studies have shown that the interaction between electrons and photons can be strengthened using specially designed nanostructures[7,8] or by using photonic cavities, which are optical microstructures that confine waves at certain 'resonant' frequencies[9]. The device reported by Henke *et al.* uses a photonic cavity to induce electron–photon coupling that is around 10,000 times stronger than that reported previously — without the need for a sophisticated (and expensive) laser system.

The design (Fig. 1) features an optical wave generated in a ring-shaped photonic cavity whose quality factor — the ratio of the time the light spends in the device to the period of its oscillation — is very high. A continuous optical wave is produced using a low-power fibre laser that is coupled to a silicon nitride circuit consisting of a waveguide and the ring cavity, which can be placed inside an electron microscope. When the frequency of the laser matches the resonant frequency of the cavity, the confined wave repeats itself after each trip around the ring, and its amplitude is enhanced by a build-up of the light field after many cycles. This enhancement is evident in sharp dips in the optical transmission spectrum of the photonic circuit at resonant wavelengths.

When an electron beam is focused on a point close to the surface of this cavity, it interacts with the light field emanating from one of these resonant modes. The strength of this interaction can be determined as a function of the position of the electron beam and the frequency of the laser by measuring the energy spectra of the electrons. This approach allowed Henke *et al.* to image the light field at the surface of the resonator with single-nanometre spatial resolution. At the same

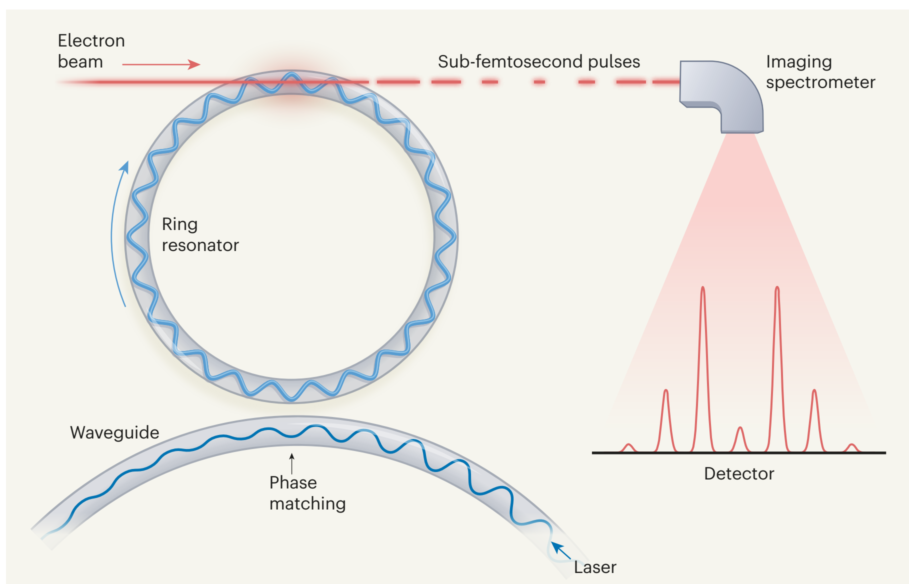


**Figure 1 | An integrated photonics platform for modulating an electron beam.** Henke *et al.*[2] designed a device comprising a low-power laser, a waveguide and a ring resonator — a ring-shaped optical microstructure that amplifies a certain 'resonant' frequency of light. Blue arrows indicate the direction of light waves; the red arrow shows the direction of electron waves. The resonant mode inside the cavity interacts with an electron beam at the cavity's surface, modulating the phase (the fraction of the waveform completed at any point in time) and energy of the electron waves at the optical frequency. The waveguide is designed to modify the light wave so that the phase velocity of the resonant mode matches the electron's velocity. When the electrons disperse after interacting with the light field, the initially continuous electron beam forms a train of pulses with durations of less than one femtosecond (1 fs is $10^{-15}$ s). An imaging spectrometer detects an energy spectrum containing peaks separated by the photon energy of the light wave.



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time, they were able to measure the energy spectrum of the resonant mode inside the cavity with a resolution of microelectronvolts. By using only a few tens of milliwatts of optical power, they broadened the spectrum of electron energies produced by the electron microscope by around 400 eV.

The interactions with photons endow these phase-modulated electron waves with special properties. After interacting with the light field and then dispersing through a vacuum in the device, electrons with higher momenta catch up with slower electrons. When this happens, the electrons cease to propagate as a single continuous beam, and instead form short pulses lasting less than one femtosecond, separated by the period of the optical wave[1]. These modulated electron beams enable attosecond metrology (1 as is $10^{-18}$ s) and experiments that can probe ultrafast electronic dynamics with high spatial resolution.

In the past year, the behaviour of these modified electron beams has been studied theoretically, and several predictions have been made — including how they will interact with systems existing in two independent quantum states[10], and how the coherence of the electron beam (the degree to which the waves are in phase with each other) could be transferred to photons emitted through a process known as cathodoluminescence[11]. Henke and colleagues' results offer a way of investigating these phenomena experimentally, which might enable control of optical excitations with the nanometre resolution provided by electron microscopes. It also puts forward a means of achieving high electron current, even in experiments with electron beams characterized by narrow energy spectra[12] — thereby opening a route for simultaneous high-resolution spectroscopy, microscopy and quantum control in the near future.

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1. Feist, A. *et al. Nature* **521**, 200–203 (2015).
2. Henke, J.-W. *et al. Nature* **600**, 653–658 (2021).
3. Kapitza, P. L. & Dirac, P. A. M. *Math. Proc. Camb. Phil. Soc.* **29**, 297–300 (1933).
4. Freimund, D. L., Aflatooni, K. & Batelaan, H. *Nature* **413**, 142–143 (2001).
5. Barwick, B., Flannigan, D. J. & Zewail, A. H. *Nature* **462**, 902–906 (2009).
6. Ryabov, A., Thurner, J. W., Nabben, D., Tsarev, M. V. & Baum, P. *Sci. Adv.* **6**, eabb1393 (2020).
7. Breuer, J. & Hommelhoff, P. *Phys. Rev. Lett.* **111**, 134803 (2013).
8. Dahan, R. *et al. Science* **373**, eabj7128 (2021).
9. Wang, K. *et al. Nature* **582**, 50–54 (2020).
10. Gover, A. & Yariv, A. *Phys. Rev. Lett.* **124**, 064801 (2020).
11. Kfir, O., Di Giulio, V., García de Abajo, F. J. & Ropers, C. *Sci. Adv.* **7**, eabf6380 (2021).
12. Krivanek, O. *et al. Nature* **514**, 209–212 (2014).

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## Forum: Medical research

# Gut clues to weight gain after quitting smoking

Research has uncovered factors that underlie the weight gain associated with cessation of smoking. Here, scientists consider the implications of this finding from the perspectives of gut biology and of smoking. **See p.713**

### The paper in brief

- **People who stop smoking usually go on to gain weight, which can cause some individuals to start smoking again.**
- **The factors underlying this type of weight gain are not fully understood.**
- **Microorganisms in the gut (termed the microbiota) can influence aspects of human health, and have been implicated in obesity.**
- **On page 713, Fluhr *et al.*[1] report evidence from studies in mice and humans that point to the microbiota as having a role in weight gain associated with the cessation of smoking.**
- **These findings might aid efforts to enable people to avoid side effects associated with quitting smoking.**

**Matthew P. Spindler & Jeremiah J. Faith**

## Gut microbial mischief

Cigarette smoking is the leading preventable cause of death worldwide, and yet many smokers never attempt to quit[2,3]. The weight gain associated with cessation of smoking is cited as a major reason why more people don't try to stop[2,3]. This weight gain is broadly attributed to smoking-associated effects on energy intake, metabolic rate and physical activity, but the specific underlying molecular mechanisms are not understood. Fluhr and colleagues now provide evidence that implicates gut microorganisms in this phenomenon.

The authors established a mouse model that replicates features of the weight change that occurs after smoking cessation in humans. These animals gained less weight during smoke exposure, and their weight returned to the non-smoking baseline after exposure ceased. The authors demonstrate that microbiota-dependent factors affect how much weight is regained. They found that administering antibiotics reduced the amount of weight regained, which suggests that a bacterial component of the microbiota targeted by antibiotics contributes to the process. This effect on the animals' weight was maintained for weeks after antibiotic administration was halted, and the results were unaffected by changes in diet or differences in the original microbiota of mice obtained from various vendors.

Fluhr and colleagues then carried out experiments to pinpoint the effect of smoke-associated microbiotas on weight change. Mice that lacked their natural microbiota (germ-free animals) and that received a transplant of faecal microbiota from mice exposed to smoke gained more weight than did animals transplanted with control microbiotas from mice not exposed to smoke. This type of weight gain was observed consistently for two recipient strains of mice lacking their natural microbiota and on two different diets, suggesting that smoke-associated microbiotas directly affect weight gain.

However, several aspects remain to be addressed before these observations can be generalized to humans. Studies in humans that compare the microbiota of smokers and non-smokers have yielded disparate results — some research indicates that the microbiota is perturbed, whereas other studies find no difference[4–6]. Fluhr and colleagues show that the microbial composition of faeces differs between mice exposed to smoke and unexposed mice, but such a distinction is less clear in human studies. Furthermore, the community of bacteria that make up the microbiota varies tremendously between individuals. Experiments establishing whether the microbiota-dependent modulation of this



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