A marriage of materials and optics

A laser-annealing technique for increasing the dopant concentration in semiconductors, the creation of a glass photonic states with short wavelengths possible by an ultra-large density of emission described by Liu et al. report that in their experiment the emitted spectrum covers the spectral range 500 nm < λ < 900 nm, peaking at the free-space wavelength 700 nm.

Despite Liu and co-workers’ impressive results, a few challenges lie ahead. The first is that the electron gun needs to be placed in a vacuum chamber so that the flying electrons are not stopped by collisions with air molecules. It will be interesting to see if in the future this constraint can be overcome and if the technology can be made fully on-chip either by using an on-chip vacuum chamber, or perhaps with a solid-state material that supports the ballistic transport of electrons.

The second hurdle is that most of the Cherenkov radiation emitted actually remains within the metamaterial. Owing to the extremely short wavelengths involved, it is not simple to efficiently extract the emitted radiation and to use it to illuminate an object in the far-field as is the case with a conventional laser device. Despite this difficulty, Liu et al. report that by using a resonant grating to outcouple the light, the power extracted from the metamaterial can exceed by two to three orders of magnitude the power that is obtained with more conventional structures. The experimental verification of broadband Cherenkov emission with such low-energy electrons is likely to open exciting new avenues in nanotechnologies, and it is easy to imagine that it will find applications in the context of particle detection, nanoscale light sources, or biomedicine.

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References
occurs on the timescale of 100 ns after laser irradiation. Thanks to such a short time of recrystallization, the discharge of Sb dopant atoms from the amorphous Ge$_x$Sn$_{1-x}$Sb is suppressed,” Takahashi told Nature Photonics. “Consequently, the Sb dopant is efficiently introduced into the Ge$_x$Sn$_{1-x}$ polycrystal.”

For laser annealing to be successful, it is important that the photon energy is much larger than the bandgap energy of Ge$_x$Sn$_{1-x}$. Under this condition, the penetration depth of the KrF excimer laser is estimated to be 6 nm in the Ge$_x$Sn$_{1-x}$ polycrystal, which means that laser annealing is limited to the surface layer. The hole-electron mobility of Sb dopant atoms from the amorphous Ge$_x$Sn$_{1-x}$Sb is 6 × 10$^{-13}$ cm$^2$ V$^{-1}$ s$^{-1}$, larger than that of bulk silicon. Pulsed laser annealing in water can, in principle, be used to introduce dopants into other crystals, such as Ge and SiC, and in the future could be used to further improve the electronic properties of integrated circuits.

In addition to laser annealing, high-power lasers are also useful for laser processing, laser photoionization and shock-wave generation. To obtain high peak power, a Q-switch is essential. However, conventional Q-switches based on electro-optical or acousto-optical effects are bulky and cannot easily be made smaller than the size of a palm, which is still too large for applications such as in a laser ignition in a vehicle engine or in a thruster in a spacecraft.

Taichi Goto from Toyoohashi University of Technology has surpassed this limitation by using a thin-film Q-switch device based on the magneto-optical effect. An approximately 200-μm-thick Tb$_{0.2}$Bi$_{0.8}$Fe$_{0.5}$Ga$_{0.5}$O$_{12}$ thin film, whose index indicates the number of oxygen vacancies, was epitaxially grown on a 560-μm-thick Gd$_2$Ga$_3$O$_{12}$ substrate. The Q-switch was made by placing the thin film between Helmholtz coils with a diameter of 5 mm. When a magnetic field of about 20 mT was vertically applied to the thin-film Q-switch, the polarization of light was rotated by about 45° due to the Faraday effect. The thin-film Q-switch was placed between a Nd:YAG crystal and a concave mirror that served as an output coupler; the Nd:YAG crystal was pumped by a diode laser (wavelength of 808 nm and output power of 32 W). By using the thin-film Q-switch, the cavity length (defined by the distance between the rear facet of the Nd:YAG crystal and the concave mirror) was reduced to just 10 mm.

The Q-switch enabled the generation of 5.2 ns pulses with a peak power of 0.25 kW. When a permanent magnet was added next to the Helmholtz coils, the voltage necessary for Q-switching was further reduced from 7.8 V to 1.1 V. Considering that the driving voltage for a conventional Q-switch based on the electro-optical effect is on the order of kV, the thin-film Q-switch based on the magneto-optical effect can also result in the use of a much smaller power-supply. “There still remain some missing pieces of the puzzle in the mechanism of the thin-film Q-switch,” commented Goto. “If we solve them, further increases in output peak power and decreases in pulse duration would be possible.”

In the field of fibre-based optical communications, second-order nonlinear optical effects are widely used for functions such as wavelength conversion or optical modulation. Currently, nonlinear optical crystals, such as LiNbO$_3$ crystals, are often integrated into glass-based optical fibres or waveguides. However, the nonlinear optical crystals have disadvantages such as refractive index matching with glass materials. To overcome the above-mentioned disadvantage, Kosuke Funajima of Tohoku University has developed a nonlinear optical glass material with a second-order nonlinear optical coefficient of $d_{22} =$ 9.6 pm V$^{-1}$. In principle, glass materials cannot possess second-order nonlinear optical effects due to their amorphous structure. However, Funajima found that glass composed of 35%TiO$_2$-45SiO$_2$ (STS45) can possess a crystal phase. By applying a thermal treatment at 940°C, a crystal phase developed from both sides of the sample towards the centre. Pyramidal TiO$_2$ units aligned in the same direction induced spontaneous polarization, yielding second-order nonlinear optical effects in the STS45.

The second-order nonlinear coefficients of $d_{11}$ and $d_{22}$ were determined as 1.7 pm V$^{-1}$ and 9.6 pm V$^{-1}$, respectively, at the fundamental wavelength of 1.064 μm. The STS45 glass exhibited high optical transparency. Specifically, at the wavelength of 1.55 μm, the optical loss was 0.6 dB cm$^{-1}$, corresponding to 99.9% optical transmission for a 1-mm-thick STS45 sample. For the next step of his research, Funajima is aiming to realize devices based on STS45, in particular, a wavelength converter based on quasi-phase-matching and an optical switch element. At this stage, the growth area and the polarization direction of the domains of STS45 are not yet controlled. In order to realize domain manipulation, we may have to apply a well-controlled stimulus, such as laser pulses, to the STS45 during the crystallization process,” Funajima told Nature Photonics. Research into topological physics with light has been receiving great attention in recent years. In particular, there have been many experimental demonstrations regarding photonic edge states, a photonic version of the quantum Hall effect for electrons. Kent’aka and Masaya Notomi from NTT Basic Research Laboratories proposed a non-trivial system composed of one-dimensionally aligned gain and loss materials (±$g_s$, ±$g_l$), and showed numerical simulations predicting the appearance of photonic edge states by parity–time (PT) symmetry breaking.

As gain and loss materials, they considered an array of lambda-scale embedded active-region photonic-crystal (LEAP) cavities (K. Takeda et al., Nat. Photon., 7, 569–575; 2013) with a wavelength-scale distance. The unit cell was composed of four LEAP cavities with different gain or loss values, $g_s$, $g_l$, $-g_s$, and $-g_l$. “Due to a cavity with small modal volume, the LEAP cavities can form a stronger coupling system than microring resonators, which are often used for the study of topological physics with light,” said Takata. “The frequency range for the coupling state of the LEAP cavity system is 100 GHz to 500 GHz, while that of microring systems is on the order of 1 GHz.”

The team’s numerical simulations exhibited a bandgap in the dispersion curve diagram between wavenumber and photon energy when the PT symmetry is broken (for example, $g_1 = 1$ and $g_2 = 0.5$). In this condition, the calculated detuning eigenvalues for a 40-LEAP cavity system showed that one singular state — photonic edge state — appeared when the LEAP cavities at both ends of the system were composed of the same, either gain or loss material. “For verification of our model, we
estimates that the magnitude of the gain and loss should range from 100 to 1,000 cm$^{-1}$, said Takata.

A non-contact optical scheme for measuring the temperature of a gas was discussed by Yukiko Shimizu from the National Institute of Advanced Industrial Science and Technology. She described the development of an optical-frequency-comb thermometer, whereby temperature is determined by the rotational constant of a molecule. As a proof-of-principle experiment, she measured the absorption spectrum of acetylene gas under a pressure of 60 Pa at room temperature by dual-comb spectroscopy. The temperature of the acetylene gas was calculated by the fitting of the obtained 50 absorption lines to the theoretical equations of the vibration–rotational transition. Given that the pressure linewidth (4.5 MHz) was smaller than the Doppler linewidth (240 MHz), the obtained absorption lines were fitted to Gaussian functions. By using this fitting method, the temperature was experimentally determined as 23.3 ± 0.87 °C; a value in good agreement with that obtained by putting a resistance thermometer on the outer wall of the gas cell (23.4 °C). “Going forward, I would like to further expand the ability of the optical-frequency-comb thermometer. The next JSAP meeting will be held in Fukuoka on 5–8 September 2017.

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LIQUID CRYSTALS

Realizing 3D topological solitons

Topological solitons are knots in continuous physical fields classified by non-zero Hopf index values. When mapped to 3D physical fields, 3D topological solitons, called hopfions, are true pearls of mathematics and topology, and physics. They are physical realizations of the celebrated mathematical Hopf fibration. However, although they are predicted to exist in different physical systems, up until now there haven’t been many reliable experimental demonstrations.

Now, Paul Ackerman and Ivan Smalyukh from the University of Colorado at Boulder, USA, introduce a method to experimentally generate and numerically analyse such localized structures in chiral nematic liquid crystals (Phys. Rev. X 7, 011006; 2017). They show that knotted field configurations can be embedded in a uniform background of a physical field as stable configurations in real physical systems. The findings will pave the way for many applications ranging from new modes of liquid-crystal displays to data storage and spintronics.

“Our research group has long-standing research interests in soft condensed-matter physics, photonics and topology, so the experimental, numerical and theoretical search for such structures was perhaps the most exciting thing we could do at the nexus of these fields,” Smalyukh told Nature Photonics.

Ackerman and Smalyukh used holographic laser tweezers to reliably generate 3D topological solitons and then explored them in detail with 3D nonlinear optical imaging. An ytterbium-doped fibre laser operating at 1,064 nm and a phase-only spatial light modulator are integrated into the holographic laser tweezers set-up. The set-up is capable of producing arbitrary 3D patterns of laser light intensity within the liquid crystals. The laser tweezers are also integrated with a 3D imaging set-up based on three-photon excitation fluorescence polarizing microscopy to enable fully optical generation, control and non-destructive imaging of the solitons.

In a similar fashion to the mathematical Hopf maps, the method demonstrated by Ackerman and Smalyukh relates all points of the medium’s order parameter space to their closed-loop pre-images within the 3D solitons. The authors showed a large diversity of naturally occurring and laser-generated topologically non-trivial solitons with differently knotted nematic fields, which previously have not been realized in theories and experiments. Their numerical modelling further provides insight into the role of the medium’s chirality, confinement and elastic constant anisotropy in enabling the stability of these 3D solitons. The authors’ findings demonstrate that chiral nematic liquid crystals will serve as model systems for experimental studies of such solitons, enabling deeper understanding.

“The ability of realizing topologically non-trivial, stable static field configurations in the optical axis orientation patterns of a liquid crystal is of great interest for many applications ranging from racetrack memories to various electro-optic and photonic devices, where optical generation of such solitons could allow for engineering new means of light–matter interactions and optical circuitry,” Smalyukh affirmed.

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