NONLINEAR OPTICS

Fibre sources in the deep ultraviolet

Wavelength-tunable ultraviolet light sources are required for a wide range of applications, but are typically difficult to manufacture and operate. A simple gas-filled optical fibre that performs efficient frequency conversion from the infrared to the deep-ultraviolet could be a promising answer.

Zhipei Sun and Andrea C. Ferrari

Wavelength-tunable deep-ultraviolet (DUV; ~200–300 nm) and vacuum-ultraviolet (VUV; ~100–200 nm) lasers are needed in fields such as lithography[1], medicine[1] and spectroscopy[2]. However, many laser sources in this wavelength range, including excimer- and ion-based DUV and VUV lasers, are complex and expensive to manufacture and operate because of their high power consumption, short lifetime, low efficiency and narrow accessible wavelength range[1]. Writing in a recent issue of *Physical Review Letters*, Nicolas Joly and co-workers now report[3] a hollow-core argon-filled photonic crystal fibre (PCF) capable of wavelength-tunable near-infrared (NIR) to DUV frequency conversion at efficiencies of up to 8%. The output wavelength of the PCF can be tuned in the range of 200–320 nm by varying the input pulse energy or gas pressure, and does not require any external realignment of the system.

One of the most compact, effective and simple ways of generating DUV and VUV light is to apply nonlinear optical frequency conversion processes such as harmonic generation[1,4], Raman[5] or four-wave mixing[6] to the output of NIR all-solid-state lasers. The conversion efficiency of the process depends primarily on the input light intensity, the length of the optical medium and its nonlinear coefficient[7]. Typical efficiencies are ~10% for commercial third-harmonic generation-based systems and ~5% for systems based on fourth-harmonic generation of an 800 nm ultrafast Ti:sapphire laser.

Converting NIR to DUV/VUV wavelengths is particularly challenging because of the narrow transparency window of nonlinear materials in the UV range. For example, beta barium borate (BBO), a nonlinear conversion crystal widely used for generating UV wavelengths, has a UV transmission cut-off wavelength of ~189 nm (ref. 1). The process is further complicated by the large group velocity mismatch between interacting pulses and the requirement for multistage conversion (for example, two cascaded second-harmonic converters to change 800 nm light into 200 nm light)[1]. There are also other limitations, including the lack of large-size and high-damage-threshold nonlinear materials, and the need for critical optical alignment and complex optical set-ups such as delay lines and dispersion compensators[5–7]. It is therefore imperative to develop novel nonlinear optical conversion techniques that exhibit high efficiency, are cheap to fabricate and can be easily integrated into existing set-ups.

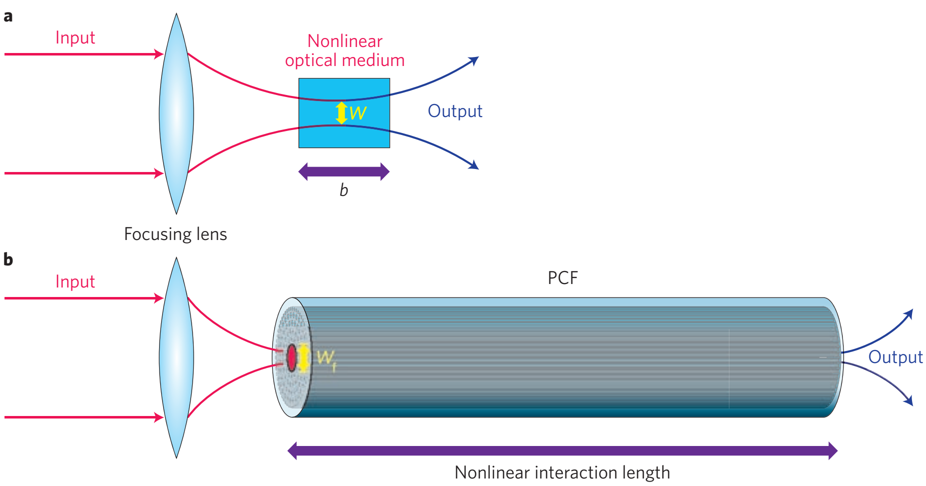

Figure 1 | Comparison of free-space and PCF frequency conversion schemes. **a**, In free-space conversion, the interaction length *b* is limited by the tight focusing required to decrease the beam waist *W* and thus increase the intensity of the beam[7,13]. **b**, In the PCF-based scheme, the nonlinear frequency conversion efficiency can be significantly enhanced by strong mode confinement combined with a long fibre length[9]. The PCF's guiding properties, such as the guided mode diameter (W_f), transparency window and dispersion, can be tailored through appropriate fibre design. Gas-filled hollow-core PCFs are more flexible than solid-core PCFs because their nonlinearity and dispersion can be varied by changing the properties of the filling gas (such as pressure) or using a mixture of different gases[3,13–15].

One promising approach is optical-fibre-based frequency conversion (Fig. 1). This compact, alignment-free technique offers high efficiency and low threshold due to the tight mode confinement and long interaction length provided by the fibre. The guided mode-field diameter can be further reduced through fibre design optimization[7,8] and, in principle, there is no limit to the interaction length, provided low-propagation-loss fibres are used. For example, a standard single-mode optical fibre (such as SMF-28) permits interaction lengths of several kilometres while maintaining low loss (~0.2 dB km^{-1} at ~1.5 μm)[8].

The key parameters that determine the propagation and interaction of light in a fibre are mode distribution, fibre dispersion, nonlinearity, propagation loss and length[8]. Attaining highly efficient nonlinear frequency conversion requires the interacting pulses to overlap in the space and time domains, which can be achieved by appropriate design of the guiding mode and fibre dispersion[7,8]. However, the optimization of conventional single-mode optical fibres is limited by their refractive index[8,9]. Such fibres are therefore normally used for frequency conversion in a narrow range around 1.5 μm, where they exhibit low loss and low dispersion[8]. Indeed, their use in the visible and UV range is severely restricted.

PCFs confine and guide light through their microstructured cross-section[9], and are attractive for optical frequency conversion[10,11] because their guiding and dispersion properties can be optimized by proper design modifications. Solid-core PCFs have been hugely successful for supercontinuum-based optical frequency conversion at visible and NIR wavelengths[10]. However, relatively large dispersion and propagation loss limits their performance at shorter DUV/VUV wavelengths[10,11].

In contrast, hollow-core PCFs, particularly those based on a Kagomé lattice (a structural arrangement consisting of interlaced triangles[9,12]), exhibit low loss, a broad transmission range and low dispersion controllable down to the DUV spectral range[9,12]. However, their nonlinear response is lower than that of solid-core PCFs because the guided light is strongly confined in the low-nonlinear-response air-filled hollow core[9]. One possible solution is to replace the air in the hollow core with a gas that has a high nonlinear coefficient, or a mixture of gases with different nonlinear properties[10–12]. For example, filling the core with H_2 improves the Raman wavelength conversion[12]. The dispersion can be further tailored by controlling gas parameters such as pressure, which allows the pulses to be finely overlapped in the time domain. Such advantages make hollow-core PCFs particularly attractive for frequency conversion in the UV range[12–14].

The wavelength-tunable DUV light generation technique reported by Joly *et al.* offers a NIR-to-DUV conversion efficiency of up to 8% using an argon-filled hollow-core Kagomé-lattice PCF[3]. The PCF has a core diameter of 29.6 μm, an inter-hole spacing of 13.4 μm and glass webs 250 nm thick. The peak conversion efficiency is achieved at a gas pressure of 9.9 bar (990,000 Pa). The output has a broad spectrum (~100 THz in the DUV range) and high beam quality. The DUV light is generated by a sequence of linear and nonlinear effects. First, the input NIR pulses are compressed through a combination of anomalous dispersion and spectral broadening induced by self-phase modulation (that is, phase modulation caused by the pulse's own intensity[8]), which causes an increase in peak power. This increase leads to a strong self-steepening effect (a shift in pulse peak due to an intensity-induced change in group velocity[8]). The spectrum is then asymmetrically extended towards the UV as a result of the frequency-dependent nonlinear coefficient of the gas. Finally, the compressed pulses release part of their energy in the form of dispersive UV waves while propagating in the gas-filled fibre. As discussed above, the frequency conversion principle in gas-filled PCFs differs from that of supercontinuum-based conversion in solid-core fibres[3,10,14]. Raman scattering, which consumes input energy for long-wavelength generation in solid-core fibres[10], is avoided in argon-filled hollow-core PCFs because argon does not have a Raman response, thus allowing more of the energy to be used for short-wavelength conversion[3]. The pressure-controllable dispersion of argon-filled PCFs[15] also allows shorter wavelengths to be generated at much higher efficiencies than in solid-core fibres[3].

The DUV generation threshold reported by Joly *et al.* is still relatively high (~1 μJ for a 20 cm PCF) and cannot directly be obtained using NIR pulses from a Ti:sapphire oscillator. However, the researchers did manage to reduce the threshold by a factor of three, with a corresponding slight increase in conversion efficiency, by using a PCF of around 1 m in length[3]. The use of even longer PCFs would further decrease the threshold, but it would also introduce disadvantages such as larger dispersion and increased propagation loss (for example, 3 dB m^{-1} for 270 nm light in the work of Joly *et al.*). These results point towards a new generation of compact and reliable DUV light sources for applications such as lithography, medicine, biology and spectroscopy. Theoretical estimations indicate that conversion efficiencies of up ~20% may be possible[14] with an ultrabroad spectrum in the VUV range[3,14]. Higher output powers and energies should also be possible, as noble gases have high damage thresholds. One exciting thought is the potential realization of an all-fibre set-up, in which a fibre-based ultrafast laser is used as the pump. ❒

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References

1. Misra, P. & Dubinskii, M. A. *Ultaviolet Spectroscopy and UV lasers* Ch. 1,7,10 (Marcel Dekker, 2002).
2. Ferrari, A. C. & Robertson, J. *Phys. Rev. B* **64,** 075414 (2001).
3. Joly, N. Y. *et al. Phys. Rev. Lett* **106,** 203901 (2011).
4. Durfee III, C. G., Backus, S., Murnane, M. M. & Kapteyn, H. C. *Opt. Lett.* **22,** 1565–1567 (1997).
5. Granados, E., Spence, D. J. & Mildren, R. P. *Opt. Express* **19,** 10857–10863 (2011).
6. Ghotbi, M., Beutler, M. & Noack, F. *Opt. Lett.* **35,** 3492–3494 (2010).
7. Saleh, B. E. A. & Teich, M. C. *Fundamentals of Photonics* Ch. 3,9,21,22 (John Wiley, 2007).
8. Agrawal, G. P. *Nonlinear Fibre Optics* Ch. 1–4,11 (Academic, 2007).
9. Russell, P. St. J. *J. Lightwave Technol.* **24,** 4729–4749 (2006).
10. Dudley, J. M., Genty, G. & Coen, S. *Rev. Mod. Phys.* **78,** 1135–1184 (2006).
11. Dudley, J. M. & Taylor, J. R. *Nature Photon.* **3,** 85–90 (2009).
12. Benabid, F., Knight, J. C., Antonopoulos, G. & Russell, P. S. J. *Science* **298,** 399–402 (2002).
13. Nold, J. *et al. Opt. Lett.* **35,** 2922–2924 (2010).
14. Im, S. J., Husakou, A. & Herrmann, J. *Opt. Express* **18,** 5367–5374 (2010).
15. Im, S. J., Husakou, A. & Herrmann, J. *Opt. Express* **17,** 13050–13058 (2009).

SUPERCONDUCTORS

Terahertz superconducting switch

The use of terahertz pulses to 'gate' interlayer charge transport in a superconductor could lead to a variety of new and interesting applications.

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Imagine a device that allows the flow of electrical charge to be switched on and off almost instantaneously and without dissipation. Reporting in *Nature Photonics*, an international team of researchers from England, Germany and Japan have now taken a step towards this goal by using electric field pulses to manipulate the superconductivity of a layered material[1]. In their experiment, a pump field causes terahertz oscillations between a three-dimensional (3D) superconducting 'on' state and a 2D 'off' state.

The idea of using a static electric field to control charge flow in a semiconductor or metal channel is relatively simple: by changing the intensity of the field, one can control the density of free carriers and therefore the conductivity of the channel.