NEW TUNABLE DUV LIGHT SOURCE FOR SEEDING FREE-ELECTRON LASERS

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Abstract

Seeding of single-pass free-electron lasers usually relies on frequency doubling or tripling of a conventional laser, or on the generation of high-harmonics in noble gases. The setups are usually rather complex and limited to specific wavelengths. Here we present a fully tunable source based on Ar-filled kagomé hollow-core photonic crystal fibre. Diffraction-limited DUV pulses of ~50 nJ and fs duration which are continuously tunable from 150 to 320 nm are generated. Seeding of SPARC-FEL is discussed.

Single-pass free-electron lasers (FEL) offer the possibility of generating short coherent pulses at very short wavelengths. In a seeded configuration, the properties of the FEL can be highly enhanced, because the coherence of the seed can be transferred to the FEL generated wavelength [1, 2]. Hence small pulse-to-pulse energy fluctuations as well as improved temporal coherence can be achieved. Moreover, the length of the undulator required is shorter than for self-amplified spontaneous-emission (SASE), which is advantageous when striving for more compact sources. Harmonics of mode-locked Ti:Sa lasers [3] or harmonics generated in gases [4] are the usual seed sources. However such techniques are limited to discrete wavelengths and require a rather complicated set-up. We propose here to employ a recently developed ultra-compact deep-UV laser source: a photonic crystal fibre filled with argon [5]. Hollow-core photonic crystal fibres (HC-PCFs) offer an effectively diffraction-free optical device where the input light can interact with gas over a very long distance [6]. In particular, kagomé-lattice HC-PCF is very promising because of its broad transmission window, permitting spectral broadening. Here we take advantage of soliton effects in such fibres to self-compress 30 fs pulses down to a few optical cycles, leading to the emission of resonant dispersive waves at phase-matched wavelengths in the UV spectral region. In contrast with conventional harmonic generation, where the converted wavelengths appear in narrow bands, the very low dispersion of the Ar-filled HC-PCF allows phase-matching over a very broad spectral range, leading to the generation of UV light tunable from 150 nm to 320 nm. We discuss here the use of such a device to seed SPARC-FEL [7].

The set-up consists of ~20 cm of kagomé-lattice PCF between two gas-cells (Fig.1). The argon pressure can be continuously adjusted from 0 to 10 bar. The fibre has a ~28 µm core diameter and low transmission loss (~1.1 dB/m at 800 nm) from 700 nm to 1.2 µm. The input pulse comes from a 30 fs amplified Ti:Sa laser system. After propagation, the UV is generated, tunable from < 200 to 320 nm by varying the gas-pressure (Fig.1c). More importantly, the UV emerges in a single-lobed mode. We measured a conversion efficiency of more than 8% from the pump wavelength to the UV [5].

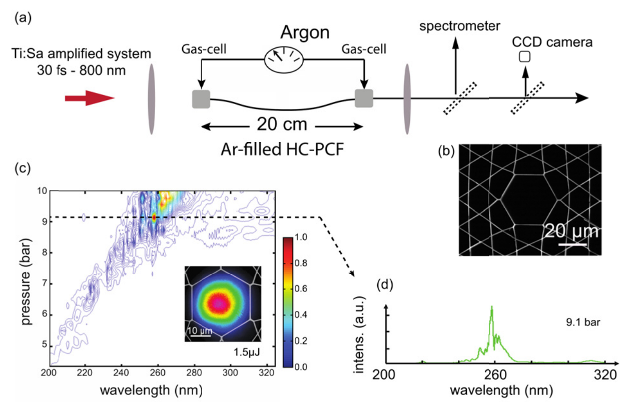

Figure 1: (a) Experimental set-up. (b) An electron micrograph of the kagomé-fibre. (c) The pressure dependence of the UV spectra at a constant input pulse energy of 1.5 µJ. (d) The spectrum recorded at 9 bar.

The dispersion of the fibre can be accurately approximated by a hollow dielectric waveguide with the same core area [8, 9]. It is plotted versus wavelength in Fig. 2a for different Ar gas pressures. The dispersion results from a balance between the normal dispersion of the filling gas and anomalous dispersion of the waveguide. If the core diameter is changed, the dependence of the zero-dispersion wavelength (ZDW) on gas pressure can also be modified (Fig. 2b).

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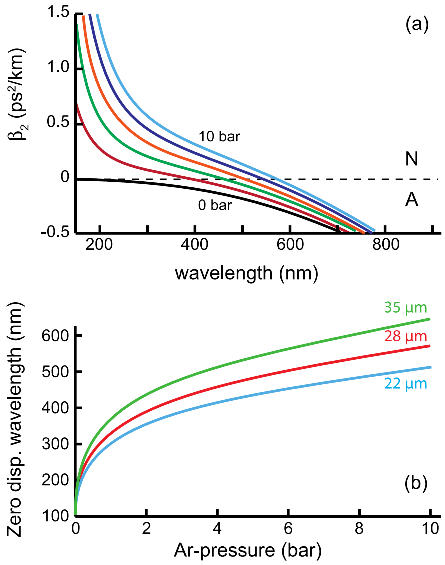

Figure 2: (a) Dispersion for a 28 µm core diameter HC-PCF filled with different pressure of argon from 0 to 10 bar by step of 2 bar. (b) The zero dispersion wavelength plotted against Ar-pressure for fibres with different core diameters.

The process can be explained by looking numerically solving the generalised nonlinear Schrödinger equation to model the propagation of the input pulse along the fibre:

$$\frac{\partial A}{\partial z} = i\gamma\left(1+\frac{i}{\omega_0}\frac{\partial}{\partial t}\right)|A|^2 A + \mathfrak{F}^{-1}\left\{\left[i\left(\beta-\frac{\omega-\omega_0}{v}\right)-\frac{\alpha}{2}\right]A(\omega)\right\} \quad (1)$$

where A is the complex envelope of the optical field, t is the time in a reference frame moving at the group velocity v of the input pulse, α is the wavelength-dependent loss, β is the axial wavevector and $\mathfrak{F}^{-1}$ is the inverse Fourier transform. The nonlinear contribution of the gas is $\gamma = n_2\omega/(cA_{\mathrm{eff}})$, where n_2 is the nonlinear refractive index, c the speed of light in vacuum and A_{eff} the effective area of the core. In our case, where the fibre has a 28 µm core diameter, $\gamma \sim 7.7\times10^{-7}\,\mathrm{W^{-1}m^{-1}}$ at 5 bar of Argon. Propagation of a 1.5 µJ, 30 fs pulse at 800 nm in this fibre filled with 5 bar of argon is presented in Fig. 3.

Initially the pulse undergoes soliton-like compression (in the time domain) due to self-phase modulation induced by the Kerr-nonlinearity and the very low anomalous dispersion of the waveguide (−0.4 ps^2/km at the pump wavelength). The shock derivative term causes the induced spectrum to extend asymmetrically into the UV region. In the second stage the compressed pulse radiates into resonant dispersive waves in the UV region. The radiation quickly separates from the residual pump due to strong group velocity walk-off (Fig. 3d). From the simulations, we can estimate that the UV pulse duration after its generation is ~10 fs. Using frequency resolved optical gating we also measured the residual pump duration after emission of UV light. Taking account of the normal dispersion introduced by the glass window at the output cell, we estimated the pulse to be 9 fs.

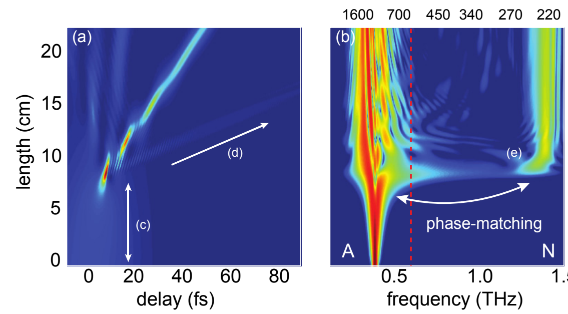

Figure 3: Time and spectral evolution of a 1.5 µJ 30 fs Gaussian pulse propagating inside 20.5 cm of kagomé-fibre filled with 5 bar of argon. Dispersive wave (d, e) is generated after ~ 5 cm of fibre (c).

In the reference frame of the soliton the emission of a dispersive wave from a soliton relies on the phase-matching condition:

$$\beta_{\mathrm{disp.}}(\omega) = \beta_{\mathrm{sol.}}(\omega) \quad (2)$$

Where the wavevector of the soliton is $\beta_{\mathrm{sol}} = \gamma P_0/2$, P_0 being the peak power of the soliton at the point of emission [10]. Since the dispersion of the filled-fibre depends strongly on the gas pressure, the phase-matching condition and consequently the wavelength of the generated UV are tunable by varying pressure. We plot in Fig. 4 the phase-matching curve (Eq. 2) for a fibre with a 28 µm core diameter, for gas-pressures from 2 bar to 10 bar in steps of 2 bar. This clearly shows the range of wavelengths accessible via this process.

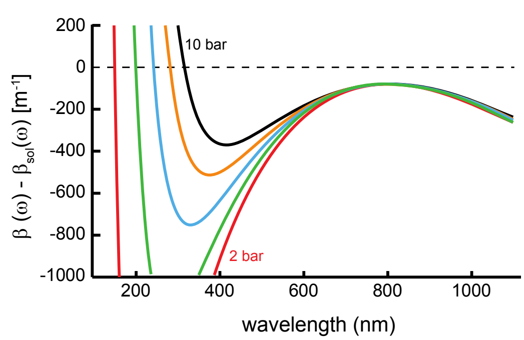

Figure 4: Phase-matching conditions between dispersive waves and a soliton created by a 1.5 µJ 30 fs pulse launched into a fibre filled with argon at different pressure ranging from 2 to 10 bar in steps of 2 bar.

To explore the potential of this new source for seeding a FEL, we used the Genesis code [11] with parameters corresponding to SPARC-FEL. Table 1 presents the

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different parameters used in our simulations, for seed pulses at 150 and 300 nm.

Table 1: parameters used for Genesis simulation in the case of seeding of SPARC-FEL

E-beam		
Energy	170 MeV	
Current	50 A	
Emittance	1.5 π.mm.rad	
Energy spread	2×10^{-4}	
Undulator		
Period	28 mm	
Nb. periods/section	77	
Nb. of sections	6	
Deflexion parameter	K = 0 to 3.4	
Seeding pulse		
Wavelength	150 nm	300 nm
Energy/pulse	<10 nJ	<80 nJ
Pulse duration	10 fs	15 fs
Peak Power	1 MW	5 MW

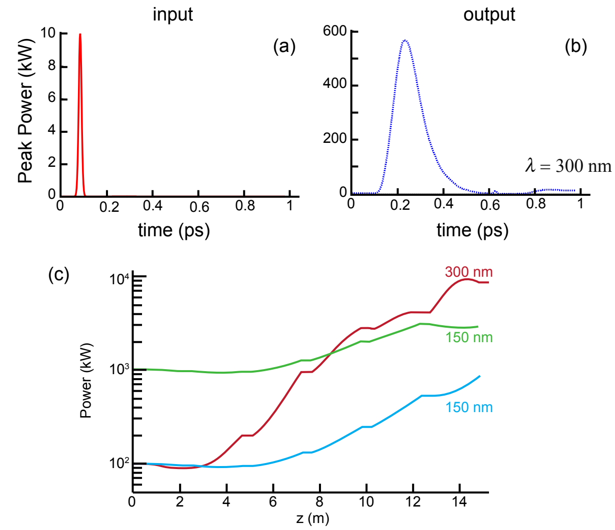

Figure 5: Simulations using the Genesis code with parameters given in Table 1.

Fig. 5 shows the main results of the GENESIS simulations. Seeding at 300 nm with an input seed of 15 fs (FWHM) duration and 10 kW peak power (see Fig. 5a), leads to efficient amplification in the FEL. Indeed, Fig. 5c (red-curve) shows exponential growth of the output power from 100 kW up to saturation at 10 MW. As illustrated in Fig. 5b, the input seed is amplified but also stretched from 15 to 200 fs (FWHM) along the undulator, essentially because of group velocity walk-off. Seeding at 150 nm with a realistic peak power of 100 kW (starting from the maximum currently achievable power of 1 MW and assuming 10% coupling between the source and the electron beam), does not lead to saturation, as shown in Fig. 5(c). Indeed, the gain is lower than at 300 nm. Saturation can easily be reached at higher gain (for instance with a higher current) or higher seeding power (see Fig. 5(c)).

In summary, we suggest that a recently developed system for the generation of deep-UV light, widely tunable by varying the gas-pressure in an argon-filled kagomé-lattice HC-PCF, can be used as a seed for FELs. The UV is always generated in the fundamental mode and conversion efficiencies of up to 8% have been measured. The set-up is extremely compact and provides access to continuously-tunable seed light from 150 to 320 nm. Simulations on SPARC-FEL show amplification over this whole spectral range, and saturation at 300 nm with conservative values of seeding power.

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