Microjoule sub-10 fs VUV pulse generation by MW pump pulses using highly efficient chirped four-wave mixing in hollow-core photonic crystal fibers

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Abstract
We theoretically study chirped four-wave mixing for VUV pulse generation in hollow-core photonic crystal fibers. We predict the generation of sub-10 fs VUV pulses with energy of up to hundreds of µJ by broad-band chirped idler pulses at 830 nm and MW pump pulses with narrow-band at 277 nm. The MW pump could be desirable to reduce the complexity of the laser system or use a high repetition rate laser system. The energy conversion efficiency from pump pulse to VUV pulse reaches to 30%. This generation can be realized in a kagome-lattice hollow-core PCF filled with noble gas of high pressure with core diameter less than 40 µm, which would enable technically simple or highly efficient coupling to the fundamental mode of the fiber.

Keywords: photonic crystal fibers, four-wave mixing, vacuum ultraviolet

(Some figures may appear in colour only in the online journal)
of 11 fs pulses at 162 nm with 4 nJ energy [15]. A method for VUV fs pulse generation with a possibly much higher pulse energy is the use of non-resonant four wave mixing (FWM) in hollow waveguides filled with a noble gas. Generation of 8 fs pulses with 1 µJ at 270 nm were reported with this method by pumping with the fundamental and second harmonic of a Ti:sapphire laser [16]. This method has been extended into the VUV range generating 600 nJ, 160 fs pulses at 160 nm using the fundamental and third harmonic of a Ti:sapphire laser as idler and pump, respectively: \( \omega_s = 2\omega_p - \omega_I \) with \( \omega_p = 3\omega_I \) and \( \lambda_I = 830 \) nm [17]. One numerical study [18] showed the potential of this method for sub-5 fs VUV pulse generation and predicted the generation of 2.5 fs pulses at 160 nm by 3 fs, 800 nm idler and narrow-band pump pulses at 267 nm. However, in this case, the VUV pulse energy is limited to the nJ range. An elemental option for high efficiency and high energy VUV fs pulse generation is chirped four-wave mixing [18] in hollow waveguides. In [19], the generation of 7 fs with 200 µJ energy by chirped four-wave mixing with broad-band spectrum, positively chirped near-infrared idler pulses and narrow-band UV pump pulses in hollow waveguides is predicted. But a standard hollow waveguide has instinctively high leaky loss which makes the hollow waveguide with core diameters less than 100 µm not applicable. For a larger core diameter the phase-matching pressure should be lower than 30 Torr resulting in a lower gain per unit length. Pump pulses with GW peak power are necessarily required in an effective nonlinear process through hollow waveguides because of its small figure of merit as well as the low phase-matching pressure. However, MW pumping could be desirable in practice to reduce the complexity of the laser system or use a high-power diode-pumped multi-MHz laser operating at multi-megahertz instead of kilohertz repetition rates that increases the signal-to-noise ratio and reduces the time required for many measurements.

As will be shown, the possibility to control dispersion in the visible and UV range combined with moderate loss and broad-band transmission in a kagome-lattice HC-PCF is of great interest for applications in ultrafast nonlinear optics demanding phase-matching conditions, remarkably here for the VUV pulse generations using four-wave mixing. In this paper, we theoretically study chirped four-wave mixing for VUV pulse generation in kagome-lattice HC-PCFs. We predict the generation of sub-10 fs VUV pulses with energy of up to hundreds of µJ by broad-band chirped idler pulses at 830 nm and MW pump pulses with narrow band at 277 nm. The energy conversion efficiency from pump pulse to VUV pulse reaches to 30%. This generation can be realized in a kagome-lattice HC-PCF filled with noble gas of high pressure with core diameter less than 40 µm, which would enable technically simple or highly efficient coupling to the fundamental mode of the fiber. The kagome-lattice HC-PCF has such struter resonant wavelengths beyond the wavelengths of the pump pulse and idler pulse. We would like to note that the kind of HC-PCF with parameters considered here is practically producible and has already been fabricated at Bath University.

The cross-section of the studied model of a kagome-lattice HC-PCF is presented in figure 1(a), in which a hollow core filled with a noble gas is surrounded by a kagome-lattice cladding and a bulk fused silica outer region. The dispersion of fused silica as well as that of argon was described by the Sellmeyer formula for the corresponding dielectric function. In figure 1(b) photographs of the cross-section of the manufactured kagome-lattice HC-PCF are shown. The kagome-lattice HC-PCF has been fabricated at Bath University and the photographs were taken at the Max-Born Institute. We want to note that in this paper the kagome-lattice HC-PCF with similar parameters as in the fabricated one (figure 1(b)) is considered.

For the calculation of the propagation constant \( \beta(\omega) \) and \( \alpha(\omega) \) of this waveguide the finite-element Maxwell solver JCMwave was utilized [10, 11, 14]. In figure 2(a) the loss coefficient is presented which is a few orders of magnitude lower than the one of a hollow silica waveguide with the same core diameter, except around the wavelengths of 1200 nm and 600 nm which coincide with the strut resonances [9, 10]. Remarkably, here it has a magnitude of below 1 dB m \(^{-1}\) at around 830 nm as well as 277 nm and 166 nm corresponding to the idler, pump and signal wavelength in the four-wave
where the phase-matching pressure is between 0.33 and 0.34 atm. In (c), the blue crosses represent the direct numerical simulations, the red solid curve is the result after averaging over inhomogeneities and the green circles are the loss of a hollow silica waveguide with the same core diameter. In (b), the red solid curve represents the transmission through 2.5 cm of the kagome-lattice HC-PCF and the green circles are the one of hollow silica waveguide with the same core diameter. In (c), the blue crosses represent the direct numerical simulations and the red solid curve is the averaged results. In (d), the dependence of the wave number mismatch \( k = 2 \beta c \) on the gas pressure is shown, where \( \omega_0 = 2 \omega_p - \omega_I \) with \( \omega_p = 3 \omega_I \) and \( \lambda_1 = 830 \) nm.

Figure 2(c) demonstrates the possibility to achieve comparatively small group velocity dispersion (GVD) at the considered wavelengths which is not achievable in conventional photonic bandgap fibers. In a real waveguide, there are longitudinal variations of the structure parameters due to manufacturing imperfections, leading to fast longitudinal variation of the propagation constant, which however will be smoothed out during propagation. This smoothing can be also performed in the frequency domain, since the position of the spikes in the loss and dispersion curves scales correspondingly with the varying structure parameters. We assume a 5% variation depth of the inhomogeneity and consider an averaged loss and GVD, as depicted by the red solid curves in figures 2(a) and (c). In figure 2(d) by the blue solid line the dependence of the wavelength number mismatch \( \delta k = 2 \beta (\omega_0) - \beta (\omega_I) - \beta (\omega_S) \) on the gas pressure is shown, where \( \omega_0 = 2 \omega_p - \omega_I \) with \( \omega_p = 3 \omega_I \) and \( \lambda_1 = 830 \) nm. One can see that the phase-matching pressure is between 0.33 and 0.34 atm and in this region of pressure the wavelength number mismatch is below 0.2 cm\(^{-1}\).

For the numerical simulations we use a generalized version of the propagation equation for the electric field strength \( E \) of forward-going waves \[11, 20]\n
\[
\frac{\partial E(z, \omega)}{\partial z} = \left( \frac{\beta (\omega) - \omega}{c} \right) E(z, \omega) - \frac{\alpha (\omega)}{2} E(z, \omega) + \frac{i \omega^2}{2 c^2 \epsilon_0 (\omega)} P_{NL}(z, \omega) \tag{1}
\]

where \( P_{NL} \) describes the nonlinear Kerr polarization as well as the photoionization-induced nonlinear absorption and phase modulation by the plasma, and \( z \) is the axial coordinate. This equation does not rely on the slowly varying envelope approximation, includes dispersion to all orders, and can be used for the description of extremely broad spectra. Since the transfer to higher-order transfer modes is small, we consider only the fundamental linearly-polarized HE\(_{11}\)-like mode. The nonlinear refractive index of argon is \( n_2 = 1 \times 10^{-19} \) cm\(^2\) W\(^{-1}\) atm\(^{-1}\).

In figure 3 the spectrogram projected onto the temporal intensity (a) and spectrum (b) for the pulses after propagating through 2.5 cm of the kagome-lattice HC-PCF with the same parameters as in figure 2 filled with argon gas at the phase-matching pressure of 0.337 atm. Here the input peak intensity is \( I_0 = I_1 = 80 \) TW cm\(^{-2}\), the input pulse duration is 300 fs and the input pump frequency is \( \omega_p = 3 \omega_I \) with \( \lambda_1 = 830 \) nm. The input idler broadband pulse stretched from 6 fs to the pump pulse duration by propagation through a piece of dispersive MgF\(_2\) glass. In 3(a) we can see three bright strips around 2.27 fs\(^{-1}\), 6.81 fs\(^{-1}\) and 11.35 fs\(^{-1}\) respectively corresponding...
to the idler frequency $\omega_I$, pump frequency $\omega_P$ and signal frequency $\omega_S$ of the four-wave mixing process. The idler strip has an upward slope and the signal strip a downward slope showing that the generated signal pulse has a negative chirp opposite to the chirp of the idler pulse. In Fig. 3(b) the output spectrum is presented. Here the peak around 166 nm shows the signal wavelength generation by four-wave mixing. The smaller peak near the signal wavelength peak is due to a cross-phase modulation. The spectral broadening of the idler is also due to a cross-phase modulation and the gap around 1200 nm in the idle spectrum is caused by the high loss of the fiber in those wavelengths as shown in figures 2(a) and (b).

Figure 4 shows the sub-10 fs VUV pulse obtained by compressing the signal pulse as in figure 3 compensating its negative chirp in propagating through a piece of dispersive MgF$_2$ glass. The red solid line represents the electric field strength of the sub-10 fs VUV pulse and the blue dotted line is the one of the input pump pulse shown here for comparison.

Figure 5 shows the inverse power nonlinearities $(\Gamma n_2)^{-1}$ of kagome-lattice HC-PCF (blue circles) and hollow silica waveguide (red squares) filled with argon gas at proper phase-matching pressures according to the core diameters. The black solid line shows a limit by the highest peak intensity of 200 TW cm$^{-2}$. The energy conversion efficiency from the pump pulse to the VUV pulse is about 30% and the VUV pulse energy is about 80 µJ.

We predict microjoule sub-10 fs VUV pulse generation by MW pump pulse using highly efficient chirped four-wave mixing in a kagome-lattice HC-PCF. Low dispersion of the area. This coefficient $\Gamma$ describes the contribution of a fiber geometry to the nonlinear phase shift $\phi_{nl} = n_2 \Gamma P_0$ that a pulse with peak power $P_0$ experiences during guiding in the given geometry with a nonlinear refractive index $n_2$ of the gas. The inverse power nonlinearities $(\Gamma n_2)^{-1}$ describe the lowest peak power needed to take a significant nonlinear effect in a waveguide. Hollow waveguides provide losses inversely proportional to the third power of their core diameters and a tolerable level of loss only for diameters larger than 100 µm, which is illustrated in figure 5 by the demonstration that the inverse power nonlinearities for the diameters smaller than 100 µm are above the intensity limit curve. For diameters more than 100 µm at least GW peak power is needed to obtain a significant nonlinear effect. However, the loss of the kagome-lattice HC-PCF is mainly determined by the cladding structure such as the strut thickness and is not greatly influenced by the core diameter, and remains a few orders of magnitude below that of a hollow silica waveguide with the same core size. Therefore as shown in figure 5 for the kagome-lattice HC-PCF the required peak power is of the orders of MW and even down to 0.01 MW.
kagome-lattice HC-PCF gives the possibility to satisfy the phase-matching condition through controlling the gas pressure. The large figure of merit and small inverse power non-linearity enable a MW pump-based highly efficient chirped four-wave mixing for VUV pulse generation. Using the model of a kagome-lattice HC-PCF with similar parameters to the one manufactured at Bath University (figure 1(b)) we numerically obtained the 80 μJ, 6 fs VUV pulse by the 240 MW pump pulse. We can use a lower pump power down to 10 MW in this fiber as shown in figure 5. Moreover decreasing the core diameter enables a lower pump power, keeping a high intensity because the loss of a kagome-lattice HC-PCF is not greatly influenced by the core diameter. A MW pump could be desirable to reduce the complexity of the laser system or use the high repetition rate laser system that increases the signal-to-noise ratio and reduces the time required for many measurements.

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