Hybrid photonic-crystal fiber for single-mode phase matched generation of third harmonic and photon triplets: supplementary material

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1. Bandgap diagram and FEM model

The band structure of the inner part of the fiber is shown in Fig. S1. It was calculated according to the analytical approach proposed by Birks et al [S1] and only represents the guidance properties of the all-solid microstructure without considering the large holes surrounding the core region.

Fig. S1. Band diagram of the internal bandgap structure. The red areas correspond to the regions where the radiation can be confined in the core. The black dashed line represents the cutoff and corresponds to

the LLF1 bulk refractive index. The blue dashed line shows the losses calculated by finite element modeling.

The bandgap structure (Fig. S1) shows where the light can be coupled to the SF6 rods (in grey) and where it cannot (in red). The dashed black line represents the cutoff, corresponding to the refractive index of the low-index material (LLF1). For wavelengths between 380 nm and 700 nm, the light is trapped in the central low-index defect of the bandgap structure. Since the phase matching critically depends on the geometry and the refractive profile of the inner microstructure of the core, we precisely measured the rod-to-rod distance using a high-resolution scanning electron micrograph (SEM). Note that the diameter of the SF6 rods cannot be directly measured from the SEM since the SF6 diffuses inside LLF1 during the fabrication process. We fitted the change of refractive index at the interface between both materials from the measurement of the phase-matched third-harmonic (TH) by fitting a Heaviside function in COMSOL Multiphysics® *flc2hc* with a step of 40 nm. The diameter of a single rod is defined as the FWHM of its refractive index curve (Fig. S2 top). The refractive index distribution of the structure is reported in Fig. S2.

To analyze the loss properties of the all-solid bandgap structure we used the finite element method, focusing only on the all-solid bandgap structure. This differs from the other FEM calculations in the main text, which take account of the full structure of the fabricated fiber. The dashed blue line in Fig. S1 shows the result of this calculation. In the fabricated fiber, light leaking from the all-solid bandgap will be guided by the surrounding step-index structure.

Numerically this is implemented by defining the domain that surrounds the inner structure as a ‘Perfectly Matched Layer’ (PML). This layer can be considered as a perfectly absorbing material to avoid back reflections from the modeled boundary of the structure, which

can cause resonances for specific fiber diameters. The absorption of the material itself is also neglected. The curve has the only purpose to locate the bandwidth with minimal confinement losses of the bandgap structure, which is at $\lambda = 480$ nm. In the fabricated fiber the radiation that is not confined by the inner bandgap will be guided by the step-index structure.

Fig. S2. (bottom) Distribution of the refractive index real part over the bandgap structure of the hybrid fiber and (top) a 1D cut along $y=0$ μm (dashed line).

2. Temperature dependence

Due to the dimensions of the inner bandgap structure it is difficult to control the production parameters sufficiently precise to achieve the desired phase matching for third harmonic. However, our structure is composed of two different materials that have slightly different thermal response. With the help of a ceramic heater we heated a short piece of fiber (~ 3 cm long) to 150°C . The spectrum of THG that we have measured was shifted by 2 nm compared to the one measured at room temperature. The results are shown in Fig. S3. The spectrum measured at room temperature presents not only a narrow peak at the expected wavelength but also a strong background towards longer wavelengths. It is possible that this background is given by not phase-matched TH radiation caused by the broadband pump radiation. Since the goal of the measurement was to measure the shift of the TH peak we used our OPG without amplification (having an 200 nm spectral bandwidth) and therefore the background width reflects the spectral width of the pump. Furthermore, due to the instability of the system with respect to

the temperature changes the coupling of the pump radiation, as well as the TH radiation, dropped in the course of heating. For this reason, we normalized the spectra to the maximum values. Since our target wavelength is 532 nm we performed the measurement using the TH generated by the first high-order mode of the pump.

Fig. S3. Spectra of THG at room temperature (blue curve) and at 150°C (red curve). The shift of the peak wavelength is 2 nm.

3. Dispersion curves

To calculate the dispersion curves for LP_{01} -like modes confined either within the all-solid bandgap or by the step-index microstructure we used FEM simulation to evaluate the propagation constant as a function of the wavelength with step of 30 nm. We then fitted the results with a polynomial function. For the LP_{01} -like mode in the inner microstructure we obtained:

$$n_{eff} = 8.4786 - 74.558\lambda + 339.41\lambda^2 - 831.72\lambda^3 + 1152.8\lambda^4 - 855.57\lambda^5 + 265.35\lambda^6$$

and for the fundamental mode confined in step index core:

$$n_{eff} = 1.7561 - 0.5899\lambda + 0.75857\lambda^2 - 0.5508\lambda^3 + 0.23064\lambda^4 - 0.05257\lambda^5 + 0.00507\lambda^6.$$

References

- S1. T. A. Birks, G. J. Pearce, and D. M. Bird, Opt. Express **14**, 9483 (2006).