# All-Fiber Optical Parametric Oscillator, Pumped by an All-Fiber Yb-based MOPA

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**Abstract:** We report on an all-fiber PCF-based optical parametric oscillator, synchronously pumped by an all-fiber Yb-doped MOPA. A pump-to-anti-Stokes conversion efficiency of 8.6% is reached at a frequency-shift of 142 THz.



**OCIS codes:** (190.4370) Nonlinear optics, fibers; (190.4970) Parametric oscillators and amplifiers

## 1. Introduction

Nonlinear wavelength conversion to short as well as long wavelengths remains an active field of research, due to the constant demand for laser-quality light at new wavelengths not directly accessible by a laser transition. Fiber optical parametric converters are of particular importance, since they allow for both up- and down-conversion with large frequency shifts [1], and since the fiber gain medium is potentially inexpensive and offers the possibility of a compact and robust all-fiber configuration. Specifically of interest is the case where a fiber optical parametric converter is pumped in the normal dispersion regime, since this allows for frequency-upconversion over several THz [2]. Recent work on optical parametric generators, operating in this regime, have reported pump-to-anti-Stokes conversion efficiencies of over 30% [3, 4], however using sophisticated pump sources due to the high threshold for conversion in this configuration.

In this respect, the alternative fiber optical parametric oscillator (OPO) looks like an attractive options [5], providing a lower threshold that facilitates pumping with much simpler pump sources and ultimately all-fiber configurations. To date, however, due to the chromatic dispersion of silica, experiments on all-fiber OPO cavities have been limited to the 1550 nm wavelength region [6]. Although photonic crystal fiber (PCF) enabled the demonstration of OPOs with virtually arbitrary pump wavelengths, an all-fiber cavity at wavelengths outside the 1550 nm region has not yet been reported.

In this paper, we report a ring-cavity PCF-based all-fiber OPO, pumped by an all-fiber master-oscillator power amplifier (MOPA) operating at 1079 nm. The OPO emits at 715 nm, i.e., well outside the wavelength range directly accessible by power-scalable fiber lasers. We reach what we believe to be the largest pump-to-anti-Stokes conversion efficiency, to date, for any fiber OPO operating at a frequency-shift in excess of 140 THz. The in-fiber conversion efficiency to 715 nm was 8.6%, limited, we believe, by fiber inhomogeneities.

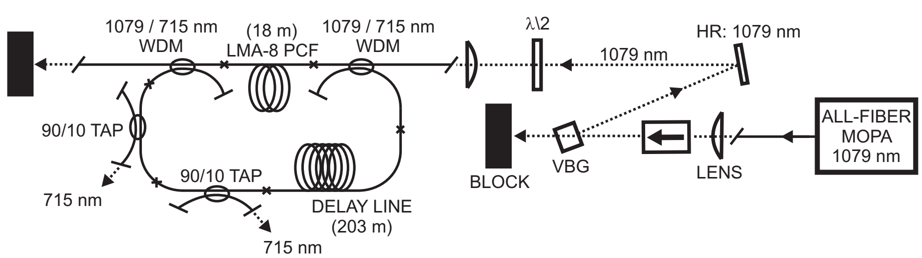


Fig. 1: Experimental set-up of the ring-cavity all-fiber OPO.

## 2. Experiment and Results

The all-fiber ring-cavity OPO is shown in Fig. 1. The linearly polarized output from the 1079 nm all-fiber pump source had a 1 ns pulselength and a pulse repetition frequency (PRF) of 1.73 MHz. Free-space coupling into the external cavity was necessitated by the requirement for a spectral filter (in this case, a volume Bragg-grating (VBG)). Filtering is crucial to avoid seeding of competing nonlinear processes such as Raman scattering. A large mode-area

PCF (*NKT Photonics LMA-8*: $\Lambda = 5.6\ \mu$m and $d/\Lambda = 4.9$) with a zero-dispersion wavelength of 1153 nm was chosen as the nonlinear converter. Both ends of the 18 m length of PCF were spliced to a WDM-coupler, to either combine or separate, the pump wave at 1079 nm and the anti-Stokes at 715 nm. A delay line, consisting of 203 m of HI1060 fiber, ensured that the round-trip time of the OPO cavity could be matched to the pump's PRF for synchronous pumping, whilst two cascaded 10% tap-couplers were used to extract 715 nm light from the cavity. The cavity round-trip loss, dominated by PCF splice-loss and fiber loss in the delay line, was estimated to 6 dB.

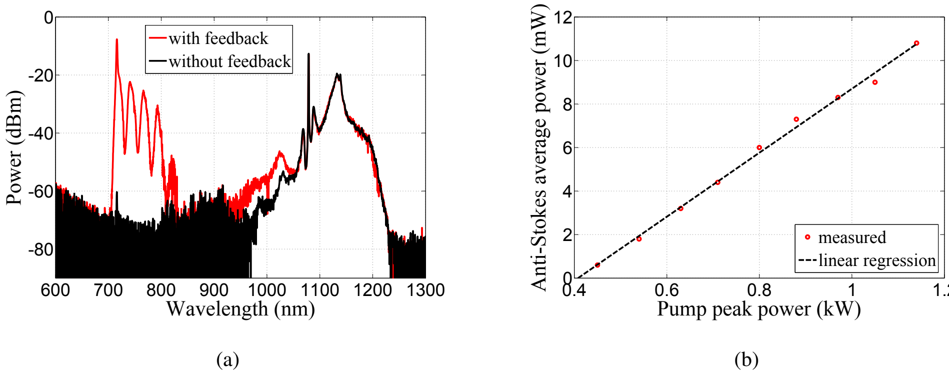


Fig. 2: (a) Influence of synchronized feedback on the OPO, as measured from the first tap-coupler (spectral resolution is 1 nm). (b) OPO output power as a function of pump peak power, as measured from the second tap-coupler.

Fig. 2(a) shows the OPO output from the first tap-coupler, for the cases with and without synchronized feedback, at a peak pump power of 0.45 kW launched into the PCF. In the absence of synchronization, the OPO effectively functions as an OPG. The single-pass anti-Stokes power at 715 nm increases by over 53 dB upon synchronization of the feedback. The anti-Stokes peak is accompanied by several orders of stimulated Raman scattering (SRS) in the wavelength range 730-830 nm. The generated SRS are pumped by the parametric anti-Stokes as the wave propagates through the delay fiber. Additionally, the 1079 nm pump generates a SRS Stokes (1132 nm) and anti-Stokes (1024 nm) as well as polarization modulation instability at a frequency-shift of 2.6 THz. These competing processes are clear indications that the parametric process, which would otherwise dominate, is suffering from inadequate phase-matching.

The use of cascaded tap-couplers resulted in strong attenuation at both 1079 nm and 1131 nm. It was therefore possible to measure the average power, contained at the anti-Stokes and its associated Raman orders, directly from the second tap-coupler. These average powers are given as a function of pump peak power in Fig. 2(b). The anti-Stokes power reaches 10.8 mW at a maximum pump power of 1.14 kW. The associated total anti-Stokes output power from both couplers is 22.8 mW, which translates to 170 mW at the PCF output. We can therefore deduce that the PCF converts 8.6% of the pump input power to anti-Stokes power. To the best of our knowledge, this result represents the highest fiber OPO conversion efficiency, for such a large frequency-shift, to date.

## 3. Conclusions

We have demonstrated an all-fiber PCF-based OPO using a simple all-fiber pump source with peak powers readily achievable with conventional robust fiber technology. Synchronous pumping in the normal dispersion regime resulted in a pump-to-anti-Stokes conversion efficiency of 8.6% at a frequency-shift of 142 THz. We believe that the conversion efficiency is currently limited by inadequate phase-matching, likely caused by longitudinal inhomogeneity in the PCF, and that further power scalability is possible with an improved fiber.

## 4. References


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