Fiber-feedback optical parametric oscillator for half-harmonic generation of sub-100-fs frequency combs around 2 μm

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We demonstrate a femtosecond fiber-feedback optical parametric oscillator (OPO) at degeneracy. The OPO cavity comprises an 80-cm-long fiber composed of a combination of normal and anomalous dispersion sections that provide a net intracavity group delay dispersion close to zero. By using a mode-locked, Yb-doped fiber laser as the pump, we achieved half-harmonic generation of 250-MHz, 1.2-nJ nearly transform-limited 97-fs pulses centered at 2090 nm with a total conversion efficiency of 36%.

Half-harmonic generation using synchronously pumped optical parametric oscillators (OPOs) at degeneracy is a promising method for extending near-infrared (IR) frequency combs to the mid-IR range [1–3]. Benefits of operating an OPO at degeneracy are large instantaneous bandwidths, low thresholds, and high conversion efficiencies. Additionally, the half-harmonic output of a degenerate OPO is intrinsically phase- and frequency-locked to the pump frequency comb [4]. Thus, half-harmonic generation can be used for efficient generation of phase-locked femtosecond mid-IR frequency combs [5] in a simple and compact setup suitable for numerous applications including molecular spectroscopy [6], high-harmonic generation [7], and dielectric laser accelerators [8].

Synch-pumped OPOs require cavities with roundtrip times matched to the repetition period of their pumps. This constraint usually results in large physical sizes for free-space implementations and imposes practical challenges for low repetition rates. For instance, in previous demonstrations, the synch-pumped degenerate OPOs required cavity lengths of several meters for operation at repetition frequencies of ≤ 100 MHz [1–3].

Another application of synch-pumped degenerate OPOs is in optical computations [9,10]. In these systems, N time-multiplexed OPOs operate in the same cavity with a roundtrip of N times the repetition period of the pump. This quickly becomes unscalable in a free-space configuration as the number of temporally separated OPOs increases, even for repetition rates in the GHz range.

One technique for reducing the size of an OPO is to change the OPO cavity length to a fractional length of the typical requirement for synchronous pumping [11,12]. This technique simultaneously changes the repetition rate of the OPO output at the cost of higher thresholds and additional amplitude fluctuations, which may be undesirable.

An alternative cavity design is to use a single-mode fiber (SMF) in the OPO resonator instead of a mostly free-space beam path. This approach can reduce the overall size of an OPO while still preserving the required round-trip time of the synchronously pumped cavity. The biggest constraints of such fiber-feedback systems are the large losses due to fiber coupling and dispersion from the fiber-feedback cavity. These losses impose an upper limit on the conversion efficiency. The fiber-feedback configuration is more appropriate for degenerate OPOs than singly resonant OPOs because degenerate OPOs can tolerate more loss given the same pump power.

Fiber dispersion also limits the operating bandwidth and the output pulse length. The fiber-feedback technique has been applied previously to synch-pumped singly resonant OPOs operating away from degeneracy [13–15]. The shortest pulses generated in these OPOs were just under 1 ps, and these pulses were limited by the narrow gain bandwidth away from degeneracy and the group velocity dispersion of the fiber-feedback loop.

In this Letter, we present a degenerate synch-pumped OPO that consists largely of a dispersion managed SMF cavity producing near transform-limited 97 fs pulses at the signal wavelength of 2090 nm. The feedback loop is comprised of two different SMF types that provide near-zero group delay dispersion (GDD) around the signal wavelength, thus preserving the broad bandwidth of the degenerate OPO and supporting sub-100-fs pulses. This OPO provides as much as 300 mW of average output power at the signal wavelength using 830 mW of 1045-nm pump power.
The setup for the degenerate fiber-feedback OPO is shown in Fig. 1. The pump source is a Menlo Systems Orange-A, mode-locked, Yb-doped fiber laser operating at 1045 nm with an output that provides 70-fs pulses at 250 MHz with up to 1 W of average power. The OPO cavity length has an 8-ns round-trip time corresponding to twice the synchronous pumping requirement. This longer cavity length was chosen to provide an additional free-space segment, thus allowing for the use of turning mirrors to optimally couple light into the fiber by using the fixed-orientation reflective collimators.

A 1-mm-long MgO:PPLN (periodically poled lithium niobate) crystal designed with a poling period of 31.8 μm provides broadband gain around the signal wavelength at degeneracy. The crystal is anti-reflection coated on both sides for the pump and signal wavelengths. The dichroic mirror (DM) is designed with high transmission (T > 96%) for the pump and high reflectivity from 1.7 to 2.3 μm (R > 99%) for the signal. The output coupler (OC) is a dielectric-coated mirror that provides high transmission (T > 65%) at the signal wavelength. We stabilize the cavity length for continuous operation by using a “dither-and-lock” technique for which we apply a small modulation around 20 kHz to the pump laser cavity length and generate an error signal from the OPO output, which is then applied to the piezoelectric transducer (PZT) of the OPO to stabilize the cavity length to the center of an oscillation peak [1].

We limited the total GDD of the OPO cavity through two methods. First, we used commercial reflective collimators that incorporate factory-set silver-coated parabolic mirrors to couple light into and out of the SMFs. Use of these mirrors avoids the chromatic dispersion associated with lenses. Second, we used a combination of two types of SMF with anomalous (Corning SMF-28e+) and normal (Nufern UHNA7) dispersion for the feedback loop. The UHNA7 fiber has a germanium-doped core and a step-index profile designed to provide normal dispersion around the signal wavelength of the OPO.

The approximate dispersion parameter, D, for the SMF-28e+ fiber is 41 ps/nm-km [16]. For the UHNA7 fiber, we estimated the dispersion parameter as -29 ps/nm-km. We measured these values by passing the 2090 nm output of a free-space cavity degenerate OPO with near transform-limited 65 fs pulses through small 10-cm lengths of each fiber and measuring the output pulses by using a second-harmonic generation frequency-resolved optical gating (SHG-FROG) setup. We compared the measured amplitudes and phases of the pulses to simulated results to estimate the approximate dispersion parameters. We conducted these measurements at low powers to reduce the effects of nonlinear effects, thus neglecting the nonlinear refractive index of the fibers.

The lengths of the two fibers were selected so that after passing through 80 cm of total fiber length, the calculated average GDD at the signal wavelength was close to zero. The fiber-feedback loop consists of two 16.5-cm segments of SMF-28e+ and one 47-cm segment of UHNA7 fiber as shown in Fig. 1. The third-order dispersion is not compensated and is the dominant source of dispersion in the cavity. Use of a high output coupler reduces the intracavity power, which itself reduces the effects of the fiber optical nonlinearities. We also used an inline fiber polarization controller (see Fig. 1) to minimize the change of polarization in the fiber and ensure maximum gain in the nonlinear crystal.

We chose a configuration of three fiber sections with two splices (instead of two sections with one splice) to keep a symmetric beam profile in the free-space portion of the cavity. The two fiber types have significantly different core sizes, thus...
matching between the two reflective collimators. Core diameters of 8.2 μm and 2.4 μm are documented for the SMF-28e+ and UHNA7 fibers at 1.5 μm, respectively; the calculated mode field diameters are 12.1 μm and 4.4 μm at 2 μm, respectively, for the two fibers giving an estimated splice loss of ~3.9 dB. By using the “fire polish” function available on a Vytran GPX-3400 glass processing system, we thermally diffused the core of the UHNA7 fiber to reduce the splice loss due to this mode mismatch. The total loss through the fiber is ∼2.6 dB. This includes ∼2 dB of coupling loss and ∼0.3 dB of loss per splice. These measurements were performed using the 2090 nm output of a free-space cavity degenerate OPO. By using the SMF-28e+ fiber as the entrance and exit fibers with the respective mode field diameter, we calculated the approximate waist size of the pump beam inside the MgO:PPLN crystal to be 11 μm.

Figure 2 shows the measured average OPO output power versus the average input pump power, when the output coupler had 65% transmission. The measured slope efficiency is approximately 72% and the maximum conversion efficiency is 36%. The threshold was 480 mW, which enabled us to pump the OPO at 1.7 times above threshold. Given that the optimum conversion efficiency is expected at a pump level of about four times above the threshold, we believe this conversion efficiency can be further enhanced by either using a higher pump power or reducing the cavity losses, such as the fiber coupling loss. This fiber-feedback OPO produced a maximum average output power of 300 mW from the OPO for roughly 830 mW of input pump power.

The characteristic interferometric autocorrelation and measured optical spectrum of the output pulses recorded at an average OPO output power of 300 mW are shown in Fig. 3. The pulse width is estimated to be 97 fs and the bandwidth 64 nm. The time–bandwidth product is approximately 0.44, which is suggestive of a nearly transform-limited Gaussian pulse. The signal pulsewidth is broader than the pump pulsewidth, thus suggesting that the GDD in the OPO is not compensated away from the signal wavelength, and this results in a limited bandwidth. The bandwidth is still very broad, which further confirms the advantage of operating the OPO at degeneracy. Stabilizing the cavity length allowed for several hours of stable operation.

To study the temporal and spectral effects of the fiber in the cavity on the degenerate OPO, we replaced the 65% outcoupler with a gold-coated mirror and placed two coated pellicle beam splitters inside the cavity to outcouple the signal at locations P1,2 (Fig. 1). The beam splitters were placed at the entrance and exit of the fiber-feedback loop. The pellicles each have a reflectance of R ≈ 15% at the signal wavelength. The oscillation threshold in this setup was 300 mW.

We measured the autocorrelation and spectrum of the output pulses from both output couplers, i.e., before and after passing through the fiber. The interferometric autocorrelation traces and normalized spectra are shown in Figs. 4 and 5, respectively, for several pump powers with estimated intracavity powers of 87, 205, and 240 mW.

As shown in Fig. 4, after passing through the fiber, the intracavity pulses have temporally broadened from the initial pulses at the entrance to the fiber, thus suggesting that the average net dispersion is not zero. Conversely, Fig. 5 shows that the spectrum has narrowed after passing through the fiber. This is consistent with the nonlinear spectral evolution of short pulses in dispersion-managed fiber links with postcompensation [17]. The intracavity pulses of the OPO could support solitons if launched in a single fiber with dispersion equal to...
the average dispersion of the fiber feedback; however, they are not strong enough to support dispersion-managed solitons [18]. Also, as the pump power is increased, the parametric gain of the PPLN increases and this leads to reshaping of the pulse and broader spectra. These results show the importance of dispersion management and the fact that we can balance the dispersion and nonlinearity of the fiber to ensure the pulse is not significantly distorted after a single pass. We were unable to use the SHG-FROG setup here because of its bandwidth limitations, which would have been beneficial to estimate the pulse shape and spectral phase.

These results also show that high outcoupling in a fiber-feedback OPO yields better pulse quality and a higher conversion efficiency mainly because of the nonlinear phase shift in the fiber, which is weaker for the smaller intracavity powers that occur with higher outcoupling. To achieve shorter pulses in a fiber-feedback degenerate OPO, a more comprehensive study of the fiber nonlinear effects is necessary. Exploiting the fiber nonlinearity and precisely designing the dispersion and nonlinear phase could lead to further broadening, signal pulses that are shorter than the pump, and even dispersion-managed solitons. As in mode-locked lasers, balancing the dispersion and SPM in the fiber may lead to soliton formation or even spectral broadening in the cavity that will result in pulses with an even broader bandwidth than the gain bandwidth of the nonlinear crystal.

Fiber losses could be further reduced by using fibers designed for operation closer to the signal wavelength. Compensating for the additional dispersion and ensuring that the average GDD vanishes after a single pass would allow for the use of achromatic lenses and reduce the fiber coupling losses. Also, the free-space length of the cavity could be minimized here to implement very compact degenerate OPOs at much lower repetition frequencies. With the advances in power scaling of femtosecond frequency combs at 1 μm [19], the presented fiber-feedback OPO provides a path toward stable high-power femtosecond frequency combs around 2 μm.

In summary, we have demonstrated sub-100-fs operation of a 250-MHz degenerate OPO at 2090 nm by using a fiber-feedback cavity comprised of two types of SMF to achieve near-zero GDD near the signal wavelength in the cavity. We produced nearly transform-limited pulses at 97 fs and 300 mW of output with a bandwidth of 65 nm.

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REFERENCES