Fiber-feedback continuous-wave and synchronously-pumped singly-resonant ring optical parametric oscillators using reverse-proton-exchanged periodically-poled lithium niobate waveguides

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We describe guided-wave singly-resonant reverse-proton-exchanged (RPE) periodically-poled lithium niobate (PPLN) waveguide ring optical parametric oscillators (OPOs) in which the feedback was provided via a single-mode fiber pigtailed to the waveguide. Wavelength selection was achieved by means of a fiber Bragg grating inside the feedback loop. The SRO threshold for the synchronously-pumped OPO was below 1 mW of average coupled pump power. © 2007 Optical Society of America

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Optical parametric oscillators (OPOs) are flexible coherent light sources based on parametric interactions inside a nonlinear crystal between a strong pump and the subsequently generated signal-idler pair \( \omega_{\text{pump}} = \omega_{\text{signal}} + \omega_{\text{idler}} \) inside a resonant cavity [1]. Since the pump power required to reach oscillation threshold (gain = loss, for a singly-resonant OPO (SRO)) decreases as the gain per unit input power increases, the large nonlinear susceptibility and tight confinement over long interaction lengths available in periodically-poled lithium niobate (PPLN) waveguides allows for low-threshold operation [2–5]. Previously demonstrated annealed-proton-exchanged PPLN waveguide OPOs have used linear standing-wave cavities either via external mirrors or dielectric coatings on the waveguide facets [2,3]. Low-threshold CW SROs as well as pulsed doubly-resonant OPOs (DROs) have been demonstrated using Ti-diffused PPLN waveguides [4,5]. These devices were pumped using C-band sources, generating mid-IR radiation.

The devices presented here represent fully-integrated CW and synchronously-pumped (synch-pumped) ring SROs using reverse-proton-exchanged (RPE) PPLN waveguides. Pump coupling as well as resonant feedback is provided via single-mode optical fiber (SMF) pigtailed to the waveguide devices. Resonant feedback via SMF was previously demonstrated in a synch-pumped bulk PPLN OPO [6]. The OPOs can be tuned over their parametric gain bandwidths via a frequency-selective element inside the feedback loop; >60 nm (>150 nm) tuning range was demonstrated around the 1558 nm (1550 nm) center wavelength for the CW (synch-pumped) OPO. While there are well-established sources available for C-band wavelengths, the device concept presented here can easily be extended to other wavelengths of interest.

A schematic of our experimental setups can be seen in Fig. 1(a). For the CW OPO, light from an external-cavity tunable diode laser running at 779 nm was coupled into a 67-mm-long RPE PPLN waveguide device containing a 49-mm-long QPM grating (16.1 μm period). The synch-pumped OPO used a mode-locked Ti:sapphire laser producing ~1 ps FWHM pulses at 775 nm with a repetition rate of 76 MHz as the pump source and a 29-mm-long RPE PPLN waveguide device containing a 11.5-mm-long QPM grating (16 μm period). To achieve synch-pumped operation, we added a fiber-coupled variable delay line to the feedback to synchronize the OPO’s cavity length and repetition rate \( f_{\text{rep}} \) to those of the Ti:sapphire laser. For convenience, we chose a feedback length correspond-
Following the analysis in [8]. This threshold can be as low as 64 mW, assuming currently best device parameters ($\eta_{\text{norm}}=110\%$/W cm$^2$, $\alpha=0.1$ dB/cm, 0.3 dB waveguide-to-fiber coupling loss per facet, 1 dB loss for in-loop components). As shown in Fig. 3(a), a small fraction of the resonant light at 1563 nm leaked through the FBG and could be monitored simultaneously with the nonresonant C-band signal at 1553 nm.

We observed single peaks at 1563 and 1553 nm on the interferometric OSA [shown in Fig. 3(b)]. Due to this optical spectrum analyzer’s resolution bandwidth limit of 7 pm, we cannot claim single axial mode operation, even though it has been shown that ring OPOs frequently run on a single axial mode [9]. Due to the finite bandwidth of our FBG (0.2 nm, 3 dB bandwidth) and small crystal temperature fluctuations ($\pm0.1^\circ\text{C}$), we observed a cyclic shift in oscillation frequency within the allowed bandwidth. Tuning of the oscillation frequency over the parametric gain bandwidth provided by the QPM structure can be achieved by replacing the fixed FBG with a tunable one. The DRO case has also been investigated by replacing the frequency-selective element with a power splitter. While the DRO threshold is significantly lower (~30 mW), stable operation has not been achieved at this point. Separation of the conjugate C-band signals and independent phase control would have to be implemented to improve DRO stability.

The initial open-loop characterization of the 29-mm-long RPE PPLN waveguide device for synchro-pumped operation was performed by recording parametric fluorescence spectra at various temperatures to measure the parametric gain bandwidth. A bandwidth exceeding 150 nm was observed at a crystal temperature of 174°C.

After establishing feedback by closing the ring cavity and adjusting the delay line, we observed SRO operation at an average coupled pump power of approximately 3 mW. The threshold predicted for a feedback length corresponding to $f_{\text{rep}}/4$ is less than 1 mW. Due to the dual-grating FBG (JDS Uniphase) used in this experiment, we observed...
two-color operation as shown in Fig. 4. This should not be mistaken for doubly-resonant operation. The generated C-band pulses had a spectral FWHM of 2 nm, which corresponds to that of a transform-limited 1.25 ps pulse, but no measurements of the pulse width were carried out.

We measured the synch-pumped OPO's output power dependence on delay line position at oscillation threshold and three times above it. Near threshold, operation could only be achieved in a relatively narrow delay range of 2.5 ps, corresponding to approximately twice the pump pulse duration [Fig. 5(a)]. This range was greatly increased above threshold [Fig. 5(b)], where stable SRO operation could be maintained over more than a 15 ps delay range. These results agree well with previous observations of bulk synch-pumped OPOs [6].

In conclusion, we have demonstrated alignment-free CW and picosecond synch-pumped PPLN waveguide SROs in a fiber-loop configuration. The CW (synch-pumped) SRO's parametric gain bandwidth exceeded 60 nm (150 nm), covering both the C- and the L-band. Other wavelength ranges can be accessed with minor changes to the current configuration. Tuning across the parametric gain bandwidth can be achieved via a simple in-line frequency-selective element. For operation a few times above threshold, the synch-pumped SRO was insensitive to cavity length fluctuations. We demonstrated two-color operation using a dual-grating FBG. Integration of the resonant feedback loop on-chip is possible by combining directional couplers and tight waveguide bends [10].

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