Synchronously pumped optical parametric oscillators in the 1.5-μm spectral region with a repetition rate of 10 GHz

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We describe optical parametric oscillators (OPOs) operating at a 10-GHz repetition rate, synchronously pumped with a 2-W 10-GHz Nd:YVO_4 laser. Unlike in a previously demonstrated 10-GHz OPO, the cavities are nonmonolithic, permitting independent tuning of the signal's wavelength and repetition rate. We have obtained as much as 353 mW of average signal output power and a tuning range as wide as 154 nm for a signal wavelength that covers the S, C, and L bands for telecom applications. We also discuss the influence of idler feedback and various aspects of monolithic and nonmonolithic multigigahertz OPO designs. © 2004 Optical Society of America

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1. INTRODUCTION

Synchronously pumped optical parametric oscillators (OPOs) have been of great interest since their first experimental demonstration in 1972.[1,2] The versatility of the concept has produced a large variety of devices of which one or several properties such as output power,[3] nonlinear media,[4,5] pulse shortening,[6] repetition rate,[7] pump source,[8] and feedback schemes[9,10] have been explored. One of the interesting properties of OPOs is their huge accessible wavelength tuning range, which can easily cover hundreds of nanometers.

Wide tuning range in the 1.5-μm spectral region is an interesting property for many applications, in particular, in the field of telecommunications. However, these applications also demand high pulse repetition rates in the multigigahertz domain, which until recently were not possible for OPOs because suitable pump lasers with sufficiently high pulse energies were not available in the multigigahertz regime. Recently a 2.5-GHz OPO based on periodically poled $LiNbO_3$ (PPLN) was demonstrated.[11] This device was pumped with an actively mode-locked semiconductor laser and a semiconductor amplifier to boost the average pump power to 0.9 W. Subsequently we demonstrated a 10-GHz OPO[7] that was pumped with a passively mode-locked diode-pumped Nd:YVO_4 laser that had been optimized for an output power of as much as 2.1 W.[12] The OPO had a monolithic cavity consisting of a PPLN crystal with dielectric mirror coatings evaporated onto the curved end faces. The monolithic approach resulted in a simple, compact, and stable device with a particularly low pump threshold.

In the present paper we describe 10-GHz OPOs with nonmonolithic cavities that make it possible to tune the pulse repetition rate independently of the output wavelength. Additional advantages of the nonmonolithic OPO are discussed in Section 4 below. So far we have achieved a tuning range as much as 154 nm wide for the signal wavelength with as much as 353-mW average signal output power. For comparison, wavelength-tunable passively mode-locked miniature Er:Yb:glass lasers have been demonstrated with tuning ranges of ≈40 nm (covering the C band for telecommunications) and repetition rates of 10 GHz (Ref. 13) and 25 GHz.[14] These devices typically generate average output power of 30 mW. Harmonically mode-locked fiber lasers[15–18] and actively mode-locked diode lasers[19] can be operated at repetition rates of 40 GHz and higher. Compared with all these types of sources, OPOs as discussed in the present paper are superior in terms of wavelength tunability and output power.

In Section 2 we describe the experimental setup of nonmonolithic 10-GHz OPOs. The results achieved are described in Section 3. The experimental achievement of an OPO that is less sensitive to idler feedback is de-

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scribed in Section 4. In Section 5 we make a detailed comparison of monolithic and nonmonolithic OPOs, and finally we state our conclusions in Section 6.

2. EXPERIMENTAL SETUP

The main challenge in a multigigahertz OPO is to exceed the pump threshold, because high repetition rates imply high average pump powers. These are difficult to generate at high repetition rates with passively mode-locked lasers because of their tendency for Q-switching instabilities.[20] Therefore in the multigigahertz regime it is necessary to minimize the OPO threshold in terms of peak pump power. Doubly resonant oscillation (with resonant signal and idler) would allow for low pump thresholds, but we prefer singly resonant oscillation (with only the signal wave being resonated) to obtain smooth tuning behavior. We then obtain a low threshold by minimizing the cavity losses and by choosing a nonlinear crystal with high nonlinearity and sufficient length.

For our OPO devices we use PPLN (from Crystal Technology, Inc., and HC Photonics Corporation) as a material with a very high effective nonlinearity ($d_{\mathrm{eff}} = 14\,\mathrm{pm/V}$; Ref. 21). For most experiments we use a crystal that is 50 mm long, 11.5 mm wide, and 0.5 mm thick. It has eight gratings with poling periods from 28.5 to 29.9 μm in step increments of 0.2 μm. The crystal is antireflection coated for the pump, the signal, and the idler wavelengths, with special optimization for the signal wavelength. We use the longest commercially available PPLN crystal that still has enough acceptance bandwidth for the pump pulses. In this way we maximize the parametric gain and minimize the oscillation threshold. (For a constant focusing parameter, the parametric gain increases linearly with the crystal length.[22]) To prevent photorefractive damage we keep the crystal in a commercially available oven (model KK1, EKSMA) at a temperature that is adjustable from 120 to 200 °C.

The OPO cavity (Fig. 1) is of a simple linear type with two cavity mirrors (with 25-mm radii of curvature). At a repetition rate of 10.10 GHz, a signal wavelength of 1550 nm, a PPLN crystal length of 50 mm, and a free spectral range of 1.12 GHz, the signal waist's radius in the center of the PPLN is 50.2 μm, resulting in a focusing parameter ξ_s (ratio of the crystal length to the confocal parameter in the crystal) of 2.31. The free spectral range of the cavity is only 1.12 GHz, so with a pump repetition rate of 10.1 GHz we have nine pulses simultaneously circulating in the cavity. Although this situation is reminiscent of harmonic mode locking, it does not introduce problems with timing jitter, as the timing of all circulating pulses is determined by the timing of the pump pulses. The advantage of the relatively long cavity is that it allows us to use a longer nonlinear crystal with correspondingly higher gain and lower threshold.

The pump beam is focused to a radius of 38 μm, corresponding to an almost optimal focusing parameter ξ_p of 2.74.[22] The first cavity mirror is antireflection coated for the pump and serves as an output coupler for the signal wave. The second cavity mirror is highly reflective for the signal as well as for the pump wavelength. The double pass of the pump pulses reduces the threshold. Both mirrors have less than 15% reflectivity for the idler wave. No idler can be extracted from the cavity because the mirror substrates are made from BK7 glass, which strongly absorbs at the idler (at 3–4 μm wavelength). The second cavity mirror is mounted upon a piezo translator for fine adjustment of the cavity length. With manual control of the piezo voltage, synchronization of the OPO with the pump laser can be achieved for a few seconds. Long-term stable operation should be possible by use of an electronic feedback system.

Before the OPO cavity, a lens with a focal length of 60 mm focuses the pump beam, and a dichroic mirror separates the pump beam from the signal output beam (Fig. 1). Because of the double pass of the pump, two isolators attenuate the backreflected pump by ≈60 dB to prevent instabilities of the pump laser. A $\lambda/2$ plate is placed before the isolators for continuous adjustment of the pump power. The optical elements between the pump laser and the PPLN crystal attenuate the pump power by ~25%.

The pump laser (Fig. 1) has already been described in detail in Ref. 12. It is a diode-pumped Nd:YVO_4 laser, passively mode locked at a 10-GHz repetition rate with a semiconductor saturable-absorber mirror[23,24] as the mode locker and optimized for relatively high output power. The laser delivers as much as 2.1 W of power in an almost diffraction-limited output beam ($M^2 < 1.2$ for both directions). The pulse length is ≈15 ps, and the optical bandwidth is 0.16 nm.

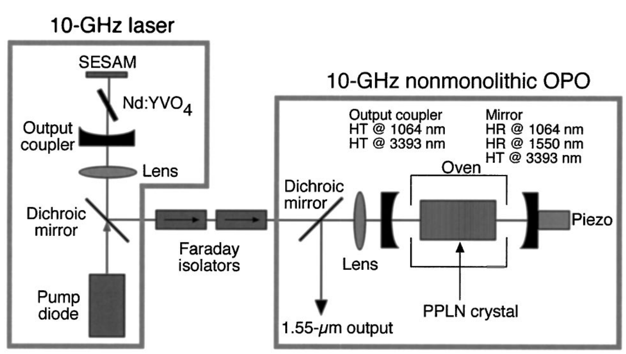

Fig. 1. Experimental setup (not to scale) of a 10-GHz nonmonolithic linear cavity OPO with a PPLN nonlinear crystal and a diode-pumped 10-GHz Nd:YVO_4 laser. HT, high transmission; HR, high reflection; SESAM, semiconductor saturable absorber; Piezo, piezoelectric transducer.

3. EXPERIMENTAL RESULTS

A. Analysis of Pump Threshold and Cavity Losses

At multigigahertz pulse repetition rates the peak power of the pump pulses is limited to typically a few watts, so the cavity losses of the OPO need to be minimized to keep the oscillation threshold sufficiently low. In a nonmonolithic configuration the parasitic signal round-trip losses arise mainly from residual reflection at the antireflection-coated PPLN crystal facets. We can estimate the reflection loss per pass through one facet to be ≈0.2%, which gives a loss of ≈0.8% per round trip for our linear cavity (with four passes through the PPLN end faces).

We determined the round-trip losses for the signal beam with a Findlay–Clay analysis[25] similar to that in Ref. 26 by measuring the peak pump power at the OPO

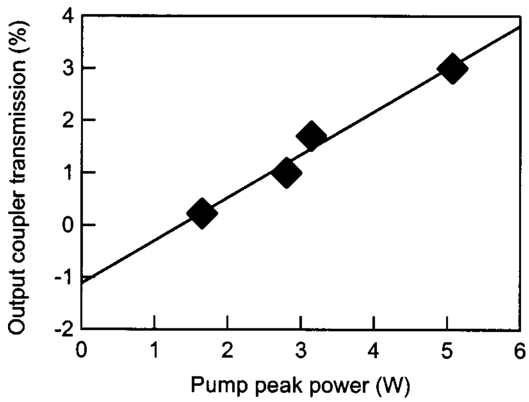

Fig. 2. Findlay-Clay analysis for the 50-mm PPLN crystal and a linear OPO cavity. Gain coefficient κ (slope), 0.82 W^{-1}; signal round-trip losses, 1.12%.

threshold, $P_{p,th}$, for various values of output coupler transmission T. In the small-gain regime the gain varies linearly with the peak pump power, and we have

$$\kappa P_{p,th} = L + T. \tag{1}$$

The round-trip losses L that we obtained are 1.12%, and gain coefficient κ is 0.82 W^{-1} (see Fig. 2). From the gain coefficient we estimate the effective nonlinearity of the crystal to be ≈8 pm/V, to be compared with a literature value of 14 pm/V.[21] Note that the beam's position in the crystal has been optimized; the nonlinearity appears to be significantly lower at less favorable positions, indicated by an inhomogeneity of the crystal material, of the poling pattern, or both. The nonlinearity may also be reduced by temperature inhomogeneities in the oven. The calculated optimum output coupling (see Ref. 26 for more details) for an incident pump power of 1.48 W is then 1.7%, in good agreement with our experimental results. For a similar OPO with a 21-mm PPLN crystal coated with the same broadband antireflection coating we found almost the same round-trip losses of 1.23%. This result suggests that the round-trip losses are due mainly to the antireflection coating and not to the PPLN crystal itself. In the 21-mm PPLN crystal OPO the gain coefficient was 0.43 W^{-1} for the same focusing parameters, ξ_s and ξ_p. This means that the parametric gain increases linearly with the crystal length, as expected for a constant focusing parameter, if temporal walk-off is not a significant factor as is the case for 15-ps pump pulses.

To determine the internal efficiency of the OPO we measured the pump depletion at the maximum pump power. The highest efficiency was obtained with 1% output coupling, where the pump depletion reached 68%. We also calculated the round-trip losses by using pump depletion and the Manley–Rowe relation, and the value of 0.94% that we obtained is in fair agreement with the previously calculated value. The same calculation with other output couplings also led to reasonable values of the round-trip losses. The Manley–Rowe relation also allowed us to estimate the total average idler power generated in the crystal to be 0.32 W with 0.353-W average signal output power.

B. Effects of Idler Feedback

As was already observed and explained for the 10-GHz monolithic OPO,[7] the response of the OPO to cavity-length changes is somewhat complicated. To summarize, it is due to an interplay of residual idler feedback and thermal effects that causes complicated variations of the signal power when the pump repetition rate is varied. Because the coating reflectivities at the idler wavelength in the monolithic OPO were not well known it was difficult to quantify the influence of the idler feedback. In the present experiments we used well-characterized mirrors, which allowed us to make calculations that included idler feedback. When the signal wavelength was 1564 nm the corresponding idler had a wavelength of 3328 nm. For a linear cavity as discussed in Subsection 3.C below, the idler reflectivity of the output coupler with 1% transmission at 1550 nm was 7.5% and the reflectivity of the second mirror (for a double pass of the pump) was ~6.5%. To calculate the round-trip losses of the idler wave we also had to take into account the transmission of the antireflection coating of the PPLN crystal, which was ~84% per facet. The reflected idler on the PPLN crystal facets did not interact with any signal pulse because of the time delay. The round-trip losses of the idler were then 26 dB. We studied the theoretically expected influence of this level of idler feedback on the pump threshold and the slope efficiency, using a numerical model for a continuous-wave OPO. The result was that the threshold power could be reduced by as much as ≈40% compared with that for an OPO with complete idler elimination if the phase of the idler reflection was ideal. The output power was also favorably influenced by the idler feedback.

Experimental results for an OPO with such a linear cavity are presented in Subsection 3.C. In Subsection 3.D we also present results for a modified OPO with reduced idler feedback.

C. Results with Linear Cavity

In this subsection we present the results obtained with a linear OPO cavity as described in Section 2 and with an output coupler transmission of 1% at 1550 nm, optimized for highest signal average output power at full pump power. The pump threshold of the OPO was 514-mW average power in 16-ps pulses, corresponding to a peak power of 2.8 W for soliton pulses. This value was achieved in the best-quality grating (grating period of 29.7 μm and temperature of the PPLN crystal of 150 °C, corresponding to a signal wavelength of 1564 nm). The threshold varied from grating to grating and even within a single grating. For each poled grating, the position of the PPLN crystal was optimized with regard to the oscillation threshold. Applying the maximum pump power of 1.48 W incident upon the PPLN crystal caused the OPO to deliver as much as 353 mW of average output power at 1564 nm. A typical autocorrelation and the corresponding optical spectrum with 353-mW signal average output power are shown in Fig. 3. The time–bandwidth product was 0.46.

The range of cavity lengths where the OPO oscillates is 380 μm wide. In this range the signal wavelength varies by less than 1 nm. By using different poled regions with periods of 28.5–29.9 μm and varying the crystal temperature from 125 to 200 °C we could tune the signal wavelength in the full range of 1467.3–1620.9 nm. The idler wavelength varies from 3871 to 3097 nm but was not measured because the idler was absorbed in the mirror substrates. The output signal power always stays above 100 mW over the complete tuning range. The tuning range of 153.6-nm width covers the whole S, C, and L telecommunication bands. A tuning range of more than 200 nm width should be achievable by careful combination of the poled grating periods, the reflection bands of the mirrors, and the antireflection coatings on the crystal. Even wider tuning ranges should be possible with special broadband mirror designs, e.g., with double-chirped mirrors.[27]

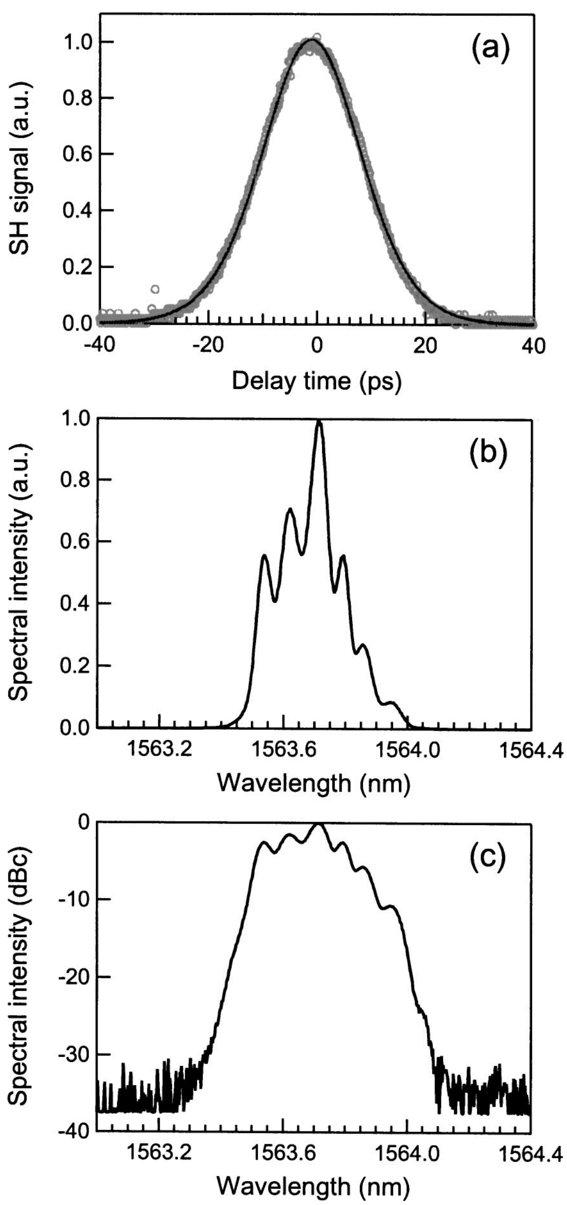

Fig. 3. (a) Autocorrelation and optical spectra on linear and logarithmic scales with 353-mW signal average output power. SH, second harmonic. The pulse length is 13.9 ps, assuming a sech^2 pulse shape. (b), (c) Optical spectrum of signal wave on linear and logarithmic scales, respectively. The spectral width is ≈0.27 nm.

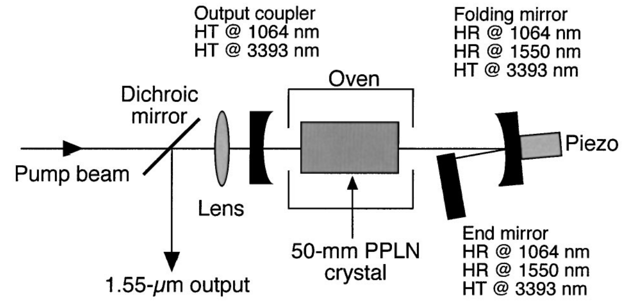

Fig. 4. Experimental setup (not to scale) of a 10-GHz nonmonolithic three-mirror cavity OPO with a PPLN nonlinear crystal and a diode-pumped 10-GHz $Nd:YVO_4$ laser. HT, high transmission; HR, high reflection.

D. Optical Parametric Oscillator with Reduced Sensitivity for Idler Feedback

Although the residual idler feedback (26-dB idler round-trip losses) helps to reduce the oscillation threshold and to improve the output power of the OPO, it leads to a somewhat critical adjustment of the cavity length, and the optimum point is lost after typically 1–2 s because of thermal drifts. To improve the long-term stability we replaced the curved end mirror of the linear cavity with a folding mirror of 100-mm radius of curvature and a flat end mirror. The additional folding mirror increased the idler round-trip losses by ≈20 dB. We still used a double pass for the pump beam. Figure 4 is a schematic of the cavity. The mode sizes in the cavity are the same as in the linear cavity, although the free spectral range is now 841 MHz, corresponding to 12 pulses simultaneously circulating in the cavity. The full angle of the beam on the folding mirror is 10°.

As expected, the OPO is far more stable with this three-mirror cavity: Optimum operation was now obtained for times of the order of 10 s without manual readjustment. Still, the output power displays several maxima when the OPO cavity length is tuned, but these maxima are significantly less pronounced. Note that this effect is significantly more difficult to suppress when a double pass of the pump is used: Even if the idler were totally eliminated at the folding mirror, the idler generated in the backward path could interfere with the nonlinear process in the forward direction. Also, there is some parasitic reflection of the pump at the input mirror, causing a Fabry–Perot effect and thus output power oscillations with the same period in the cavity length. Without the double pass of the pump, the achieved level of idler suppression would probably already be sufficient.

A Findlay–Clay analysis[25] (see Fig. 5) indicated intracavity losses of 0.95%, comparable to those of the linear cavity, 1.12%. The pump threshold was significantly increased, however, and the gain coefficient was only 0.39 W^{-1}, compared with 0.82 W^{-1} for the linear cavity OPO. This reduction of gain was somewhat stronger than expected from the reduced idler feedback. Consequently the maximum average output power was also reduced.

With the best poled grating (grating period of 29.7 μm and PPLN crystal at 150 °C) the maximum signal average output power of 103 mW was reached with 1% output coupling and the pump depletion reached 33% with a pump power of 1.36 W incident upon the PPLN crystal. We fully characterized the OPO with 0.43% output coupling transmission, where the threshold was lower, namely, 610 mW with 15.4-ps pulses. With 1.36 W of average pump power incident upon the PPLN crystal the OPO delivered 63 mW of average signal power. The pump depletion was 37%. The optical spectrum and the length of the signal pulses were similar to those obtained with the linear cavity. We also tuned the signal wavelength by varying the PPLN crystal's temperature and the grating period. In this case the temperature was varied from 120 to 200 °C and the signal wavelength could be adjusted from 1466.1 to 1620.2 nm (3879 to 3099 nm for the idler), resulting in a signal-tuning range of 154.1 nm (see Fig. 6). More than 26 mW of average signal output power was emitted over the complete tuning range. Oscillation of the OPO was possible over a 400-μm-wide range of cavity lengths.

In conclusion, reduced idler feedback led to a significantly more stable behavior, but the OPO threshold became twice higher and the output power three times lower. A higher pump power or a shorter pump pulse duration or both would be desirable for this device.

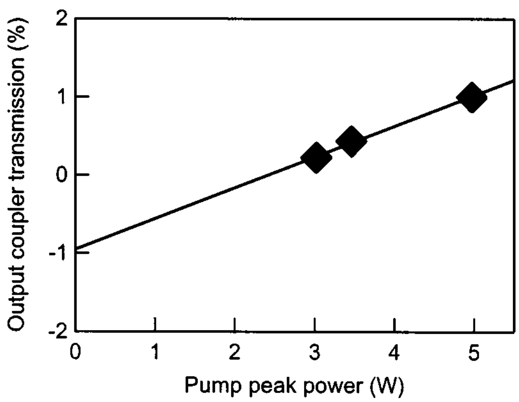

Fig. 5. Findlay–Clay analysis for the 50-mm PPLN crystal and the three-mirror OPO cavity. Gain coefficient κ (slope), 0.39 W^{-1}; signal round-trip losses, 0.95%.

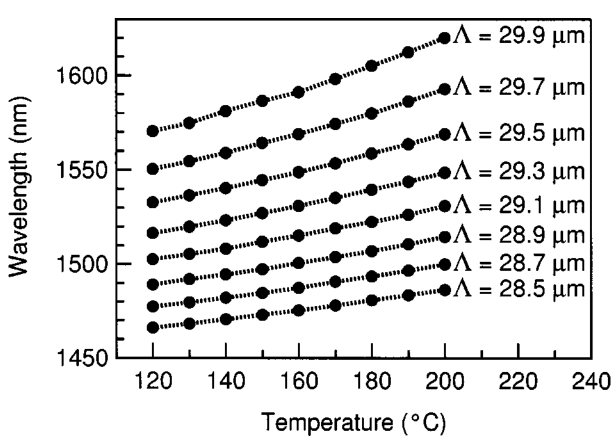

Fig. 6. Wavelength tuning of the parametric oscillator. By crystal temperature and poling period we can reach any wavelength in the range 1466.1–1620.2 nm. Filled circles, experimental data connected by straight lines. Λ is the grating poling period.

4. COMPARISON OF THE NONMONOLITHIC AND MONOLITHIC CAVITIES

In this paper we have discussed in detail OPOs based on nonmonolithic cavities with air spaces between the PPLN crystal and the cavity mirrors. In contrast, the first 10-GHz OPO[7] was based on a monolithic cavity with dielectric mirror coatings evaporated onto the curved crystal faces. In what follows, we compare these two approaches, both of which employed a double pass of the pump beam.

The monolithic OPO produced as much as 100 mW of average output power (580 mW of pump power) in 12.7-ps pulses at 1555.3 nm and had a pump threshold of 330 mW with 20-ps pump pulses. With a similar monolithic device the signal wavelength was temperature tuned from 1535 to 1578 nm.[7] The free spectral range of the OPO cavity was 3.3 GHz, corresponding to a crystal length of 20.8 mm.

A major advantage of the nonmonolithic design concerns wavelength tuning. The nonmonolithic OPO is far more versatile because one can achieve tuning both by selecting gratings with different poling periods and by changing the crystal temperature. In the monolithic design the device contains just a single poled grating, and only temperature tuning is possible, limiting the tuning range to 43 nm for the device demonstrated.[7] Another drawback of a monolithic OPO concerns the repetition rate of the device. The length of the cavity determines the repetition rate and cannot be adjusted after manufacturing. In addition, wavelength tuning by altering the crystal's temperature causes tuning of the repetition rate. We measured a change of 35 MHz of the repetition rate for a temperature change of 90 °C (corresponding to the wavelength-tuning range mentioned above).[7] Of course this limitation does not exist in the nonmonolithic approach, for which the cavity length can be adjusted independently.

Increased flexibility of the nonmonolithic OPO also results from the possibility of exchanging and independently characterizing the cavity mirrors and the crystal. It is evident, however, that a monolithic OPO is more compact and mechanically more stable against misalignment and vibrations.

In terms of losses and thus of the oscillation threshold, the monolithic OPO has a clear advantage. Parasitic losses result only from absorption and scattering in the nonlinear crystal, apart from some losses at the highly reflecting mirror. We estimate the total parasitic losses to be below 0.2%, although this is difficult to prove experimentally. In contrast, we have ≈1.1% parasitic losses per round trip in the nonmonolithic OPO with a linear cavity, which result mainly from the antireflection-coated interfaces.

To obtain temperature stable coatings with high reflectivity for two different wavelengths on a PPLN crystal is itself a challenge. With several monolithic OPOs we observed detachment of the output coupler coating when the crystal was heated above 140 °C. Because this coating must be highly reflective for the pump and the signal waves it is quite thick (~6.1 μm), and the mismatch of the thermal expansion coefficients between the coating materials (SiO_2 and TiO_2) and the lithium niobate crystal led to fracture. This problem does not exist for the nonmonolithic OPO, for which we have only a thin antireflection coatings on the PPLN crystal.

As discussed above, idler feedback is a major issue for stability of an OPO. In monolithic OPOs the idler round-trip losses are of the order of 10 dB and still strongly influence the OPO. With this cavity design it seems difficult to reduce the idler feedback substantially by using better coating, particularly if this has to be achieved in a large wavelength range. For comparison, the idler attenuation per round trip for the nonmonolithic three-mirror OPO is ~46 dB. Further idler attenuation would easily be possible, e.g., by insertion of additional folding mirrors with low idler reflectivity. Another possibility would be to insert one or two thick Brewster-angled BK7 plates in the cavity to absorb the idler wave. The effect of parasitic pump reflections could also be reduced by an additional folding mirror on the pump side.

5. CONCLUSIONS

Nonmonolithic high-repetition-rate OPOs have various advantages over the previously demonstrated monolithic 10-GHz OPOs. We have demonstrated several 10-GHz repetition-rate OPOs based on a nonmonolithic cavity and obtained picosecond pulses in the spectral range near 1.55 μm. Such a device with a 50-mm long PPLN crystal and a linear cavity generated as much as 353 mW of average output signal power. By translating the crystal and varying its temperature we tuned the signal wavelength from 1467.3 to 1620.9 nm, covering the S, C, and L telecommunication bands with a single device. The signal's average output power was more than 100 mW over the complete tuning range. The OPO was fully characterized, showing very low signal round-trip losses of 1.12%. To reduce the detrimental influence of idler feedback on the tuning behavior, we improved the idler suppression by inserting a folding mirror. For future devices, even stronger idler suppression and suppression of parasitic pump reflections (for a double pass of the pump) appear to be desirable. We have proposed different methods to achieve this suppression in a standing-wave cavity. Another method would be to use a ring cavity as described in Ref. 11: This should result in the best idler suppression, no effects from parasitic pump reflections, and lower signal round-trip losses but cannot utilize a double pass of the pump, so the threshold would be higher.

Aside from many advantages, the nonmonolithic OPO with good idler suppression has the disadvantage of a higher pump threshold. At a 10-GHz repetition rate a state-of-the-art passively mode-locked laser with ≈2 W of average output power in 14-ps pulses is just sufficient to exceed this threshold well. For higher repetition rates we will either have to increase the peak pump power or further decrease the OPO threshold. We hope to increase the peak pump power somewhat mainly by reducing the pump pulse's duration with further optimization of the pump laser. The OPO threshold may be further reduced, e.g., by use of an output coupler mirror with lower transmission (sacrificing some efficiency) or by use of a crystal material with higher nonlinearity, such as periodically poled stoichiometric $LiNbO_3$.[28]

A signal wavelength of ~1.3 μm would also be interesting for telecom applications. However, it would requires a shorter pump wavelength, as otherwise the idler would be in a strongly absorbing wavelength region of PPLN. A possible pump source would be a passively mode-locked optically pumped surface-emitting semiconductor laser emitting near 960 nm; such devices have been demonstrated to be capable of producing high powers in short pulses at high repetition rates.[29,30]

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