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Rapid infrared wavelength access with a picosecond PPLN OPO synchronously pumped by a mode-locked diode laser

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Abstract. We theoretically and experimentally investigate wavelength tuning of synchronously pumped optical parametric oscillators (OPOs) on changing the cavity length or the pump-repetition rate. Conditions for rapid and wide-range wavelength access are derived. Using an OPO pumped directly by a mode-locked diode-laser master-oscillator power-amplifier (MOPA) system, an all-electronically controlled access to near- and mid-infrared wavelengths is demonstrated. The singly (signal) resonant OPO is based on periodically poled lithium niobate (PPLN) and emits 8 ps idler pulses at a repetition rate of 2.5 GHz in the wavelength range 1986 to 2348 nm (signal: 1530 to 1737 nm). Wavelength tuning over 114 nm (signal) and 189 nm (idler) is achieved solely by electronically varying the repetition rate of the diode-laser oscillator over 720 kHz. By controlling the repetition rate with a programmable driver, an arbitrary emission sequence of the OPO on two wavelength channels is generated, with access times as short as 10 μs. 11 OPO wavelengths equally spaced in the range 1627–1689 nm (signal) or 2054–2154 nm (idler) could be addressed.

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Synchronously pumped optical parametric oscillators (SP OPOs) are important sources of ultra-short picosecond or femtosecond pulses in the near and mid infrared. Normally, SP OPOs are tuned over a wide range of tens or even hundreds of nanometers by tuning the pump wavelength [1] or by changing the temperature of the nonlinear crystal [2]. However, a practical disadvantage of these methods is that tuning is usually very slow. Faster tuning can be achieved by piezo-tuning of the OPO cavity length whilst holding the repetition rate of the pump pulses constant [3, 4]. In this paper, we demonstrate extremely rapid tuning of an OPO over wide optical ranges, by all-electronically controlled variation of the repetition rate of the diode-laser master-oscillator power-amplifier (MOPA) system used as pump laser.

In Sect. 1 we theoretically investigate wavelength tuning of SP OPOs via the repetition rate of the pump laser. We derive equations which describe the range and speed of OPO tuning by this method, and which explain which properties of the pump laser and of the OPO result in a fast and wide-range OPO tuning. The tuning range is given by the amplification bandwidth of the OPO crystal, which depends on crystal length and dispersion characteristics. For any given output wavelength the bandwidth can be maximised by choosing a suitable combination of pump wavelength, quasi-phase-matching material, and poling period. The speed with which the OPO output wavelengths can be tuned is increased by using a short crystal with a small dispersion coefficient for the resonated signal (or idler) pulses, and a pump laser with rapidly changeable repetition rate.

In Sect. 2 we describe the experimental setup of a PPLN OPO which is synchronously pumped directly by an actively mode-locked diode-laser MOPA system with an ultra-high repetition rate of 2.5 GHz. Experimental results are presented in Sect. 3. The output wavelengths can be tuned around 1.65 μm (signal) and 2.1 μm (idler). Fast tuning of the OPO signal and idler wavelengths is achieved through solely changing the repetition rate of the diode-laser system. The switching speed between two OPO wavelength channels was investigated by using a programmable radio-frequency (RF) waveform generator, which gives rapid and controlled access to different pump-laser repetition rates. Programmable emission sequences of the OPO on two wavelength channels 6 nm apart is demonstrated, with switching time shorter than 10 μs. Switching of the OPO wavelengths between 11 channels equally spaced in the range 1628–1689 nm (signal) or 2054–2154 nm (idler) was achieved.

1 Wide and rapid OPO tuning via repetition rate or cavity length: theory

It has been observed that the wavelength of a synchronously pumped OPO varies due to changes of the OPO cavity length [4]. If the cavity length is tuned out of optimum syn-

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chronism, the signal and idler pulses seek to adjust their group velocities in the crystal (and thus their wavelengths), in order to maintain the optimum temporal overlap and resynchronise with the pump pulses. This effect has been used to stabilise the cavity length [5]. In the case of low dispersion in the cavity, the SP OPO output parameters (such as spectrum, pulse duration and shape, as well as output power) show a very complex dependence on the cavity length. In this case, a precise prediction of the output characteristics as a function of the cavity length requires comprehensive numerical modelling [3], such as split-step Fourier algorithms, to properly include also pulse-shaping effects due to parametric gain and higher-order dispersion. However, in this contribution we concentrate on the contrary case of SP OPOs with a significant amount of dispersion in the cavity. In our experiment, the lowest-order dispersion effect, which is the group-velocity mismatch, is dominant such that the tuning speed and range can be calculated using a much simpler model.

In the following, we derive corresponding equations in which tuning of the OPO is determined by the dispersion of the resonant wave in the nonlinear crystal. These equations are used to calculate the wavelength tuning of the OPO as a function of the pump-repetition rate or, alternatively, as a function of the cavity length. From the equations it follows that wavelength tuning by variation of the pump-repetition rate enables much higher tuning rates than is possible by tuning via the OPO cavity length. A comparison to the experiment (Sect. 3) shows an excellent agreement with theoretical calculations.

1.1 Repetition-rate tuning with fixed OPO cavity length

We define the wavelength-tuning rate R_S as the variation of the centre wavelength of the signal pulses per time interval, i.e. $R_S = d\lambda_S/dt$. To obtain quantitative results, let us consider a singly resonant SP OPO with a signal resonant cavity of fixed length. For convenience, we assume that the OPO has a ring resonator, as was used in our experiment. We note, however, that the following equations can easily be adapted to linear cavity OPOs. The cavity roundtrip frequency, CRF, of the signal pulse is given by the length, L_C, of the nonlinear crystal and the distance, L_{AIR}, that the pulse has to travel through air during each roundtrip,

$$\mathrm{CRF} = \frac{c}{L_{AIR} + L_C n_g(\lambda_S)} \tag{1}$$

where c is the speed of light in vacuum and $n_g(\lambda_S)$ is the so-called group index of the signal pulse. As a function of the signal wavelength the group index is given by $n_g(\lambda_S) = n(\lambda_S) - \lambda_S dn/d\lambda_S$, where $n(\lambda_S)$ is the index of refraction of the nonlinear crystal. The condition for synchronous pumping is that the pump-pulse repetition rate, F_{REP}, equals the CRF of the cavity, F_{REP} =CRF. Note, however, that synchronous pumping is achieved as well, if F_{REP} is a multiple q of the free spectral range (FSR), i.e.

$$F_{REP} = q \times \mathrm{CRF}\,, \tag{2}$$

such that q is the number of signal wave pulses travelling in the OPO cavity. Inserting (2) into (1) and solving for λ_S gives the OPO signal wavelength, λ_S, as a function of the pump-laser repetition rate F_{REP}:

$$\lambda_S = \tilde{n}_g \left(\frac{1}{L_C} \left[\frac{qc}{F_{REP}} - L_{AIR} \right] \right)\,, \tag{3}$$

where $\tilde{n}_g$ is the inverse group-index function (wavelength as a function of group index). Taking the definition of R_S and expanding

$$R_S \equiv \frac{d\lambda_S}{dt} = \frac{d\lambda_S}{dF_{REP}} \frac{dF_{REP}}{dt}\,, \tag{4}$$

one can insert (3) to calculate the signal wavelength tuning rate R_S as a function of the rate dF_{REP}/dt at which the repetition rate F_{REP} of the pump laser is changed. For the first factor, one derives with some analysis:

$$\frac{d\lambda_S}{dF_{REP}} = -\frac{qc}{L_C} \left(\frac{dn_g}{d\lambda_S} \right)^{-1} \times \frac{1}{F_{REP}^2}\,. \tag{5}$$

Inserting (5) into (4) shows that R_S depends on two independently scalable factors,

$$R_S \equiv \frac{d\lambda_S}{dt} = A\,B\,, \tag{6}$$

where the first factor A depends solely on the properties of the OPO setup used. Calculating the derivative of the group index in factor A yields

$$A = \frac{q}{L_C} \left(\frac{\lambda_S}{c} \frac{d^2 n}{d\lambda_S^2} \right)^{-1} = \frac{q}{L_C} D_\lambda^{-1}\,, \tag{7}$$

where D_λ is the so-called dispersion coefficient. An optimisation of factor A is straightforward: the maximum tuning rate, R_S, is achieved with a short crystal at signal wavelengths where D_λ is small, i.e. close to the point of inflection of the refractive index, where $d^2n/d\lambda_S^2 = 0$.

As opposed to this, the second factor B in (5) contains properties of the pump laser only, namely the absolute value of the pump-repetition rate and the speed with which it can be changed:

$$B = \frac{1}{F_{REP}^2} \frac{dF_{REP}}{dt}\,. \tag{8}$$

To discuss the implications of factor B on the tuning rate R_S, let us consider two different types of pump lasers, the first one having a high-finesse laser cavity, and the second type having a low-finesse cavity.

Typical representatives of the first type (high-finesse cavity) are solid-state lasers, such as Nd:YAG or Ti:sapphire lasers. Here, a change of the repetition rate requires changing the optical roundtrip length of the laser cavity, L_{LASER}, by an amount dL_{LASER}, irrespective of whether the laser is actively or passively mode-locked. Changing the optical length of the laser at a rate of dL_{LASER}/dt, e.g. by moving a mirror with a piezo-transducer, results in a change of the repetition rate of

$$\begin{aligned} \frac{dF_{REP}}{dt} &= \frac{d\mathrm{FSR}_{LASER}}{dt} \\ &= -\frac{c}{L_{Laser}^2} \frac{dL_{LASER}}{dt} = -\frac{F_{REP}^2}{c} \frac{dL_{LASER}}{dt}\,, \end{aligned} \tag{9}$$

where $\mathrm{FSR_{LASER}} = c/L_{\mathrm{LASER}}$ is the free spectral range of the laser cavity. Equation (9) shows that, for a given rate $\mathrm{d}L_{\mathrm{LASER}}/\mathrm{d}t$ at which the laser cavity length can be tuned, the repetition rate changes faster for large values of F_{REP}, i.e. for short laser cavities. Inserting (9) into (8), the factor F_{REP}^2 cancels out, and together with (6) this results in

$$R_{\mathrm{S}} = -\frac{q}{L_{\mathrm{C}}}\left(\lambda_{\mathrm{S}}\frac{\mathrm{d}^2 n}{\mathrm{d}\lambda_{\mathrm{S}}^2}\right)^{-1} \times \frac{\mathrm{d}L_{\mathrm{LASER}}}{\mathrm{d}t}\,. \tag{10}$$

This means that the tuning rate of an OPO pumped by a high-finesse type of laser depends only on the length and dispersion of the OPO crystal and on the rate at which the laser-cavity length is changed. The OPO tuning rate is, however, independent of the length of the laser cavity and the corresponding repetition rate.

As the second pump-laser type, we discuss lasers having low-finesse cavities. Typical representatives of such lasers are diode lasers whose large gain enables large output coupling of several tens of percent. Of particular interest are diode lasers that are actively mode-locked by a modulation of the injection current via a RF driver [6]. The optical pulse repetition rate of these lasers can be varied at a constant cavity length, while the output power, centre wavelength, and duration of the pulses remain unchanged. The repetition rate can be adjusted simply by varying the frequency of the RF driver. The speed with which the repetition rate can be changed, $\mathrm{d}F_{\mathrm{REP}}/\mathrm{d}t$, depends only on the RF-driver technology. From (6) and (8) one can conclude that the fastest OPO tuning will be achieved with a diode pump laser which has a high factor $F_{\mathrm{REP}}^{-2} \times \mathrm{d}F_{\mathrm{REP}}/\mathrm{d}t$, which corresponds to a diode laser with a long (external) cavity and a rapidly tunable RF driver.

To make the meaning of (4) clearer, let us quantitatively compare the OPO tuning rate R_{S} achieved with a standard high-finesse pump laser to the OPO tuning rate expected for a diode pump laser. The basic properties of both systems are summarised in Table 1.

The left-hand column of the table considers an OPO synchronously pumped by a mode-locked, $F_{\mathrm{REP}} = 80\,\mathrm{MHz}$ repetition rate, 20 ps pump laser at a wavelength of 1064 nm. We assume the OPO to be based on a $L_{\mathrm{C}} = 38$ mm-long PPLN crystal inside a ring cavity with a FSR of 80 MHz, which is resonant for a signal wavelength of $\lambda_{\mathrm{S}} = 1550\,\mathrm{nm}$. Repetition-rate tuning of the pump laser requires a variation of the cavity length. Using a piezo-drive for one of the mirrors, one obtains a maximum rate of $|\mathrm{d}L_{\mathrm{LASER}}/\mathrm{d}t| =$ 10 µm/ms, which is a typical upper limit for piezo-transducers. This corresponds to a repetition-rate tuning of $|\mathrm{d}F_{\mathrm{REP}}/\mathrm{d}t| =$ 0.213 kHz/ms. From the PPLN Sellmeier equation given in [7] we obtain $\mathrm{d}^2n/\mathrm{d}\lambda_{\mathrm{S}}^2 = 1.60 \times 10^{-8}\,\mathrm{nm}^{-2}$ (at a crystal temperature of 150 °C). With (10), the signal tuning rate is then $R_{\mathrm{S}} = 10.6$ nm/ms (absolute value), which corresponds to a signal (and idler) frequency tuning rate of 1.35 THz/ms.

This result can be compared to the diode-pumped system described in detail in Sect. 3 The relevant data is given in Table 1, right-hand column. With the diode laser, the pump-repetition rate can be changed by $|\mathrm{d}F_{\mathrm{REP}}/\mathrm{d}t| =$ 10 000 kHz/ms, by electronically changing the RF-driver frequency. Using (6), (7), and (8) the signal wavelength tuning rate yields $R_{\mathrm{S}} = 1030$ nm/ms (absolute value), which corresponds to a signal frequency tuning rate of 130 THz/ms. This means that pumping an OPO with a diode laser is expected to result in a 100 times faster OPO tuning than what is expected for a typical solid-state laser, even for maximum piezo-tuning speed.

Table 1. Properties of solid-state-laser-pumped PPLN OPO and diode-laser-pumped PPLN OPO, for comparison of the expected signal wavelength tuning rates. For an explanation of the symbols, please refer to the text

	Solid-state-laser-pumped PPLN OPO	Diode-laser-pumped PPLN OPO
λ_{P}	1064 nm	927 nm
F_{REP}	80 MHz	2488 MHz
$\mathrm{d}F_{\mathrm{REP}}/\mathrm{d}t$	0.213 kHz/ms	10 000 kHz/ms
λ_{P}	1550 nm	1550 nm
OPO FSR	80 MHz	1244 MHz($q = 2$)
PPLN, L_{C}	38 mm	38 mm
$\mathrm{d}^2n/\mathrm{d}\lambda_{\mathrm{S}}^2$	$1.60 \times 10^{-8}\,\mathrm{nm}^{-2}$	$1.60 \times 10^{-8}\,\mathrm{nm}^{-2}$
$R_{\mathrm{S}} = \mathrm{d}\lambda_{\mathrm{S}}/\mathrm{d}t$	10.6 nm/ms	1030 nm/ms

1.2 OPO cavity-length tuning

Instead of varying the repetition rate of the pump pulses, one can also consider tuning of the OPO wavelength by changing the OPO cavity length, while the pump-repetition rate remains constant. As with the laser cavity, one can use a piezo-transducer moving with a speed of $\mathrm{d}L_{\mathrm{AIR}}/\mathrm{d}t$. Using (1), (2), and (3) in analogy to the calculations described above, one derives:

$$\frac{\mathrm{d}\lambda_{\mathrm{S}}}{\mathrm{d}L_{\mathrm{AIR}}} = -\frac{1}{L_{\mathrm{C}}}\left(\frac{\mathrm{d}n_{\mathrm{g}}}{\mathrm{d}\lambda_{\mathrm{S}}}\right)^{-1}\,, \tag{11}$$

and expanding $R_{\mathrm{S}} = \mathrm{d}\lambda_{\mathrm{S}}/\mathrm{d}t$, we finally obtain

$$\frac{\mathrm{d}\lambda_{\mathrm{S}}}{\mathrm{d}t} = \frac{\mathrm{d}\lambda_{\mathrm{S}}}{\mathrm{d}L_{\mathrm{AIR}}}\frac{\mathrm{d}L_{\mathrm{AIR}}}{\mathrm{d}t} = \frac{1}{L_{\mathrm{C}}}\left(\lambda_{\mathrm{S}}\frac{\mathrm{d}^2n}{\mathrm{d}\lambda_{\mathrm{S}}^2}\right)^{-1}\frac{\mathrm{d}L_{\mathrm{AIR}}}{\mathrm{d}t}\,. \tag{12}$$

From this equation, one expects fast tuning if the crystal is short and the signal wavelength is close to the point of inflection of the refractive index, and if the piezo-transducer moves quickly. Thus, the parameters that determine the tuning speed are basically the same as with repetition-rate tuning. Inserting the values of the example in Table 1 ($L_{\mathrm{C}} = 38$ mm, $\mathrm{d}^2n/\mathrm{d}\lambda_{\mathrm{S}}^2 = 1.60 \times 10^{-8}\,\mathrm{nm}^{-2}$, $|\mathrm{d}L_{\mathrm{AIR}}/\mathrm{d}t| =$ 10 µm/ms), (12) yields a signal wavelength tuning rate of 10.6 nm/ms at 1550 nm, corresponding to a frequency tuning rate of 1.35 THz/ms. The tuning speed obtained by tuning the OPO cavity length is therefore the same as calculated for a high-finesse-laser-pumped OPO, but almost 100 times slower than for a diode-laser-pumped OPO.

1.3 Tuning range

The wavelength range over which the OPO can be tuned by varying the pump-repetition rate (or the cavity length of the OPO) is given by the spectral width of the phase-matching condition. Here, we assume the general case that quasi-phase matching (QPM) in first order is provided by a periodically poled nonlinear crystal of length L_{C} and a QPM grating period Λ. The parametric gain profile is then proportional to $\mathrm{sinc}^2(\Delta k' L_C/2)$ (plane-wave approximation, [8]), with the effective phase-mismatch

$$\Delta k' = 2\pi \left(\frac{n_P}{\lambda_P} - \frac{n_S}{\lambda_S} - \frac{n_I}{\lambda_I} - \frac{1}{\Lambda} \right) \tag{13}$$

where $n_{P,S,I}$ is the wavelength-dependent index of refraction and $\lambda_{P,S,I}$ is the wavelength of the pump, signal, and idler waves, respectively. The function $\mathrm{sinc}^2(\Delta k' \times L_C/2)$, and thus the parametric gain, is maximum in the case of quasi-phase-matched interaction, $\Delta k' = 0$. For a given wavelength combination (λ_P, λ_S^*, λ_I^*) quasi-phase matching can always be achieved by using a suitable grating period, Λ which is calculated by setting the left-hand side of (13) to zero. The OPO can also be operated at a different signal wavelength λ_S which is not phase-matched ($\Delta k'(\lambda_S) \neq 0$), thus having a lower parametric gain, i.e. an increased pump power at threshold. The maximum detuning of the signal wavelength depends on the ratio γ_P of available pump power to minimum ($\Delta k' = 0$) pump power at threshold. More specifically, the signal wavelength λ_S with maximum detuning from the phase-matched wavelength λ_S^* is given by solving

$$\gamma_P = \mathrm{sinc}^{-2}\left(\Delta k'(\lambda_S) L_C/2\right) \tag{14}$$

for λ_S. In the case of $\gamma_P = 2$, this task becomes equivalent to calculating the parametric gain bandwidth (half-width at half-maximum), $|\lambda_S - \lambda_S^*|$. An analytical solution of (14) can be derived by using a Taylor expansion of $\Delta k'(\lambda_S)$ around the quasi-phase-matched signal wavelength λ_S^*, which yields in first-order approximation:

$$\Delta k'(\lambda_S) = \mathrm{d}\Delta k'/d\lambda_S \left(\lambda_S - \lambda_S^*\right) , \tag{15}$$

where the derivative $\mathrm{d}\Delta k'/\mathrm{d}\lambda_S$ is taken at λ_S^*. Denoting the inverse function of sinc^2 with $\underline{\mathrm{sinc}^2}$ and inserting (15) into (14) one derives:

$$\left|\lambda_S - \lambda_S^*\right| = \left| \underline{\mathrm{sinc}^2}\left(\frac{1}{\gamma_P}\right) L_C \left(\frac{\mathrm{d}\Delta k'}{\mathrm{d}\lambda_S}\right)^{-1} \right| . \tag{16}$$

The maximum detuning becomes large, if $\mathrm{d}\Delta k'/\mathrm{d}\lambda_S$ is small, approaching even infinity if $\mathrm{d}\Delta k'/\mathrm{d}\lambda_S = 0$. Around signal wavelengths fulfilling this condition, one expects widest tunability of the SP OPO output wavelengths through a variation of the pump laser repetition rate, as described above. These signal wavelengths are obtained by using (13) to calculate the derivative $\mathrm{d}\Delta k'/\mathrm{d}\lambda_S$ for a given pump wavelength:

$$\frac{\mathrm{d}\Delta k'}{\mathrm{d}\lambda_S} \equiv \frac{2\pi}{\mathrm{d}\lambda_S^2} \left(n_S - n_I + \lambda_I \frac{\mathrm{d}n_I}{\mathrm{d}\lambda_I} - \lambda_S \frac{\mathrm{d}n_S}{\mathrm{d}\lambda_S} \right) = 0 \tag{17}$$

A well-known solution of (17) is the case of wavelength degeneracy where $\lambda_S = \lambda_I$ (assuming identical polarisations for the signal and idler waves, i.e. type-I phase-matching). Thus a maximum OPO tuning range (around degeneracy) can be achieved at any signal wavelength, if the appropriate pump wavelength of half the signal wavelength is available. We note, however, that there is a second, off-degeneracy solution of (17), which provides a wide OPO tuning range also at other pump wavelengths. For further calculations, we assume that $\gamma_P = 2$, so that the maximum tuning range is identical with the parametric gain bandwidth.

In Fig. 1A, the signal and idler wavelengths for maximum gain bandwidth (maximum tuning range) are plotted as a function of the pump wavelength. The degenerate case is depicted in Fig. 1A as the straight line. The spectral bandwidth (half-width at half-maximum, HWHM) at degeneracy is plotted in Fig. 1B as the solid curve. Its variation with the pump wavelength is strongly dependent on the type of nonlinear crystal [9]. In our calculations, we assumed a 20 mm-long PPLN crystal, using the Sellmeier coefficients in [7]. It can be seen that the HWHM gain bandwidth varies in the range 3.6 (at $\lambda_P = 500$ nm) to 42 THz (at $\lambda_P = 950$ nm). Such huge gain bandwidths look promising for wide tuning of a SP OPO via the pump-repetition rate. There are, however, severe disadvantages when operating at degeneracy. Firstly, the OPO cavity becomes doubly (signal and idler) resonant, which is known to lead to power and spectral instabilities [10]. Secondly, each of the envisioned OPO wavelength ranges requires a pump laser at a wavelength of one-half of the OPO wavelength.

A method to obtain a wide gain bandwidth without these disadvantages is to consider the nondegenerate solutions of

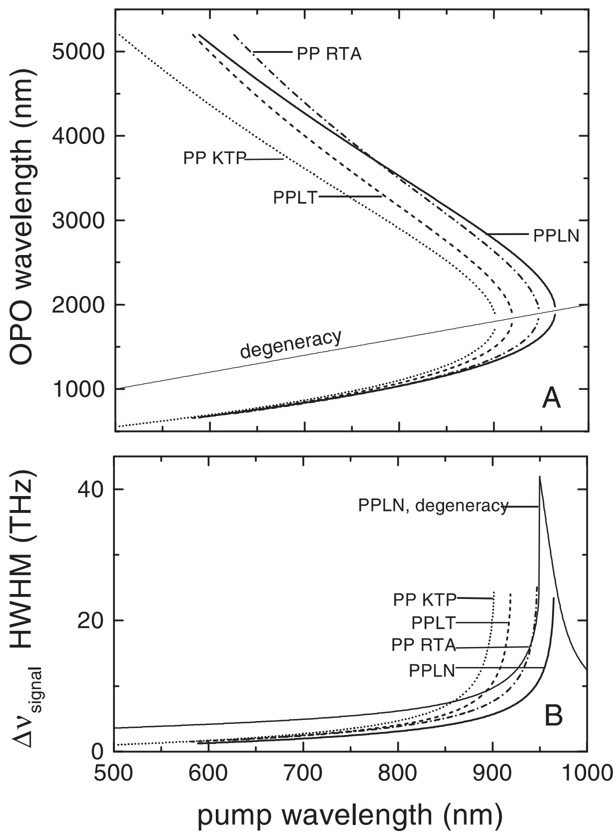

Fig. 1. **A** Signal/idler wavelengths where $\mathrm{d}\Delta k'/\mathrm{d}\lambda_S = 0$, calculated as a function of the pump wavelength for different crystals. In order to obtain a maximum parametric gain bandwidth for a given signal or idler wavelength, the optimum combination of nonlinear crystal and pump wavelength can be chosen from this diagram. **B** Half-width at half-maximum (HWHM) of parametric gain bandwidth for 20 mm-long QPM crystals of various materials, calculated for the wavelengths in **A**, as a function of the pump wavelength. The calculations are based on the Sellmeier coefficients in [8] (PPLN, 150 °C), [12] (PPLT, 150 °C), [13,14] (KTP, 25 °C), and [15] (RTA, 25 °C)

(14), where $d\Delta k'/d\lambda_S$ is zero. Such nondegenerate solutions exist in the range of normal dispersion ($dn/d\lambda < 0$), if the index of refraction as a function of the wavelength has a point of inflection, where $d^2n/d\lambda^2 = 0$. Note that this is the same condition as for achieving rapid OPO tuning via the pump-repetition rate or via the OPO cavity length, as stated by (10) and (12).

Figure 1A shows the nondegenerate solutions of (14) as a function of the pump wavelength. For comparison, the calculations were performed with the Sellmeier data of various different QPM materials (PPLN [7], PPLT [11], PP KTP [12, 13], and PP RTA [14]). Similarly, the calculated gain bandwidth is plotted in Fig. 1B, assuming a crystal length of 20 mm.

Figure 1 can now be used in the following way: in graph 1A, one selects at the vertical axis a signal or idler wavelength around which a large gain bandwidth is desired. Then the curves can be used to determine the required pump wavelength. For this particular pump wavelength, the gain bandwidth of a 20 mm-long crystal can be read from Fig. 1B. It can be seen that for any signal or idler wavelength in the range 870 nm to 4.5 μm, the required pump wavelength is within the emission range of a Ti:sapphire laser (700–1000 nm). The corresponding grating period is calculated from (13), as described above. Furthermore, Fig. 1B shows that the parametric gain bandwidth can become extremely large, depending on the choice of the signal or idler wavelength. For example, at idler wavelengths around 1930–2350 nm the HWHM bandwidth of a 20 mm-long PPLN crystal is more than 10 THz, which corresponds to more than 100 nm and is achieved with pump wavelengths in the range 945 to 965 nm. Note that this range of wide OPO gain bandwidth can be accessed not only with a Ti:sapphire laser, but also with GaAlAs and InGaAs diode-pump lasers [15–17], which emit in the range 750 to 980 nm.

To summarise, we have theoretically investigated the wavelength tuning of synchronously pumped OPOs achieved through variation of the pump-laser repetition rate. For both OPO parameters of interest, namely the signal (idler) wavelength tuning speed, and the spectral width of the tuning range, we derived equations that help to maximise these parameters. Furthermore, we can conclude that high-speed tuning, as well as wide tuning ranges, are expected for synchronous pumping of an OPO based on PPLN by RF mode-locked GaAlAs or InGaAs diode lasers. Corresponding experimental results are presented in the following section.

2 Experimental setup of diode laser pumped picosecond OPO

2.1 The diode laser pump source

The pump source is an InGaAs diode master-oscillator power-amplifier (MOPA) system (Fig. 2). The mode-locked oscillator is based on a single-stripe, distributed Bragg reflector (DBR) diode in an external cavity configuration [18]. The Bragg section of the diode is at one end and acts as one of the cavity mirrors, while the second section of the diode provides gain. Light is coupled out of the gain section through a facet which is anti-reflection coated with a high-quality dielectric coating. The resonator is completed by an external

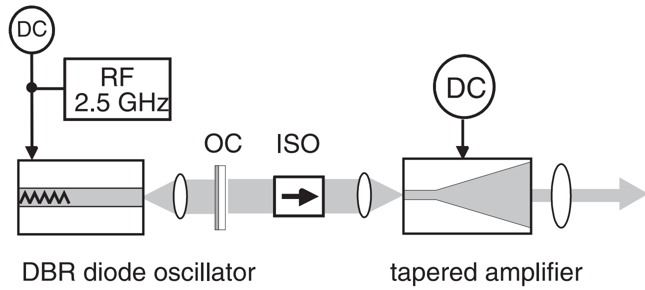

Fig. 2. Experimental setup of the diode-laser master-oscillator power-amplifier (MOPA) system used to pump the PPLN OPO. The master-oscillator is a distributed Bragg reflector (DBR) diode laser with an external 50% feedback mirror (output coupler, OC). The diode laser is actively mode-locked by modulating the injection current with a 2.5 GHz RF driver, to produce picosecond pulses at 927 nm. The diode-laser average output power of 17 mW is transmitted through a 60 dB optical isolator (ISO) and amplified to 1 W average power by a semiconductor power-amplifier (PA) with tapered geometry of the active layer

plane output coupler with a reflectivity of 50%. The output wavelength of the free-running DBR diode (without external feedback) peaks at 927 nm. The diode oscillator is actively mode-locked by adding a strong RF signal of 27 dBm to the 80–140 mA DC bias on the active region through a bias-T (signal generator Rhode and Schwarz SMP 22). The RF signal is nominally set at a frequency of 2.488 GHz, twice the FSR of the external mirror cavity. The pulse autocorrelation fits best a sech^2 pulse shape. The shortest pulses were obtained at a DC bias current of 80 mA. Under these conditions, pulses of 15 ps duration with a spectral bandwidth of 0.16 nm (56 GHz) were generated, with an average output power of 7 mW.

The pulse-repetition rate of the DBR diode can be varied simply by changing the frequency of the RF signal, which does not require any realignment of the external cavity mirror. Interpolations from measurements with RF-frequency detunings of up to 50 MHz confirmed that on changing the RF frequency by 1 MHz, the pulse duration and the spectral bandwidth should change by less than 1.5%.

The oscillator output is amplified in a single pass through a high-power semiconductor tapered amplifier which is driven by a DC current of 2.2 A. An optical isolation of 60 dB was provided between the oscillator and amplifier. In order to saturate the amplifier, we used an average input power of up to 17 mW from the oscillator. The amplified pulses were measured to have a pulse duration of 20 ps and a bandwidth of 0.45 nm. The maximum average output power was 1 W in a near-diffraction-limited beam. The output radiation from the mode-locked MOPA was shaped with a cylindrical telescope and focused into the OPO cavity with a spherical lens.

2.2 The PPLN SP OPO

The general performance of the system has been described elsewhere [17], which is why only a brief summary is given in this section. The setup of the diode laser pumped PPLN SP OPO is shown in Fig. 3. The OPO consists of a PPLN crystal in a four-mirror ring cavity. The crystal is 38-mm long with a domain grating period of $\Lambda = 26.2\,\mu$m. The

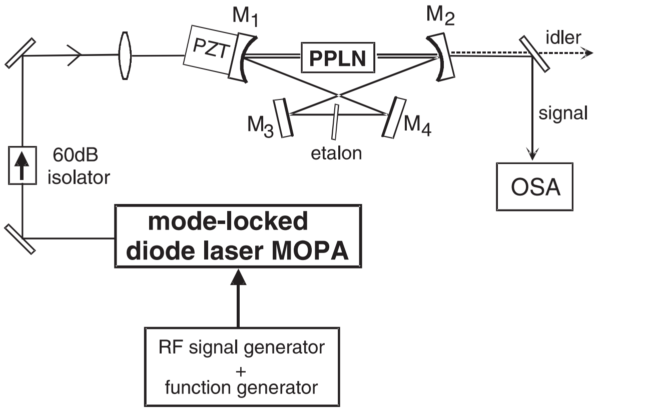

Fig. 3. Experimental setup of the OPO synchronously pumped by a diode-laser system. The pulse-repetition rate of the actively mode-locked diode MOPA is controlled by a 2.5 GHz RF driver, the frequency of which is fine-tuned with a programmable function generator. The OPO consists of a four-mirror signal resonant ring cavity (mirrors $M_1 - M_4$) and a 38 mm-long PPLN crystal. The cavity length is tuned with a piezo-transducer (PZT). For some of the experiments, a glass etalon was placed in the OPO cavity. The signal wave is analysed with an optical spectrum analyser, OSA

crystal facets are broadband anti-reflection coated for pump wavelengths at 915–935 nm ($R < 0.5\%$) and for signal and idler radiation at 1600–2300 nm ($R < 0.6\%$). It is positioned at the beam waist between two spherical mirrors, M_1 and M_2 (each with a 50 mm radius of curvature), and the cavity is completed by two plane mirrors, M_3 and M_4. The angle of incidence at all mirrors is 13°. The OPO cavity has a free spectral range of 1.244 GHz, which is one-half of the repetition rate of the diode-pump laser. Mirror M_1 is mounted on a piezo-electric transducer for fine-tuning of the resonator length. Singly resonant oscillation is ensured by using mirrors with a high reflectivity for the signal wave ($R > 99.8\%$ between 1560–1770 nm) but with high transmission for both pump and idler waves ($T = 99\%$ at 927 nm, $T > 98\%$ between 2.07–2.19 nm). The confocal parameter of the resonator mode in the crystal is 30 mm (signal beam waist 60 µm). At the secondary beam waist between mirrors M_3 and M_4, a glass etalon was inserted into the OPO cavity for some of the experiments. This etalon was uncoated and had a thickness of 150 µm and a free spectral range of FSR= 660 GHz, corresponding to 6 nm at a wavelength of 1.6 µm.

The average pump power at threshold of the OPO was 350 mW. With 870 mW of pump power incident on the crystal, the average output power was 75 mW for the idler wave (in a single beam) and 5 mW for the signal wave (at each mirror). With an etalon inserted in the OPO cavity, the pump power at threshold increased slightly to 400 mW and the maximum average idler output power was 60 mW. The signal power residually transmitted through the highly reflecting cavity mirrors was 4 mW per mirror. The OPO idler wave pulse durations were measured by a collinear autocorrelation technique using a 19-mm-long PPLN crystal with an acceptance bandwidth of 190 GHz. The FWHM of the autocorrelation trace is 12 ps, which corresponds to a pulse duration of 8 ps (assuming a sech^2-shaped intensity profile). The spectral bandwidth of the pulses was measured to be 0.6 nm (40 GHz), thus yielding a time–bandwidth product of 0.32 (Fourier-limited).

3 Tuning characteristics of the diode-pumped OPO

3.1 OPO wavelength tuning via the cavity length

Figure 4A shows the output wavelengths of the OPO as a function of the cavity-length detuning. For this measurement, the crystal temperature of 151 °C, the repetition rate of 2.487 GHz, and the pump wavelength of 927 nm are held constant. The OPO tunes in the ranges 1638–1684 nm (signal) and 2062–2136 nm (idler) almost linearly with the cavity length, with a rate of $\mathrm{d}\lambda_\mathrm{S}/\mathrm{d}L_\mathrm{AIR} = 1.62\,\mathrm{nm}/\mu\mathrm{m}$, corresponding to a frequency tuning rate of 180 GHz/µm. This measured tuning rate can be compared with the theoretical value calculated by using the Sellmeier equations given in [7] and the crystal length of 38 mm. From (11), one obtains a theoretical value of $\mathrm{d}\lambda_\mathrm{S}/\mathrm{d}L_\mathrm{AIR} = 1.69\,\mathrm{nm}/\mu\mathrm{m}$, which is in very good agreement with the experiment.

The tuning range through cavity tuning as shown in Fig. 4A is limited by the maximum translation of our piezo-transducer ($\mathrm{d}L_\mathrm{air} = 29\,\mu\mathrm{m}$). The simultaneously recorded idler output power is shown in Fig. 4B. It can be seen that at both ends of the tuning range the idler power remains above a level of 70% of its maximum value. This observation suggests that a wider tuning range would be achieved using a piezo-transducer of increased translation.

Using a saw-tooth voltage at maximum driving speed, the entire tuning range shown in Fig. 4A was covered in less than 100 ms. This corresponds to a maximum translation speed of $\mathrm{d}L_\mathrm{AIR}/\mathrm{d}t = 0.3\,\mu\mathrm{m/ms}$, and thus a signal wavelength tuning rate of $R_\mathrm{S} = 0.5\,\mathrm{nm/ms}$. A further increase of the cavity-length tuning speed would be restricted to values of typically 10 µm/ms due to the resonance frequency of the piezo-driven mirror. Above this speed, addressing OPO wavelengths accurately becomes difficult due to mechanical phase shifts in the mirror movement and due to hysteresis effects in the piezo-transducer. Note, however, that the tuning rate of $R_\mathrm{S,CAVITY} =$

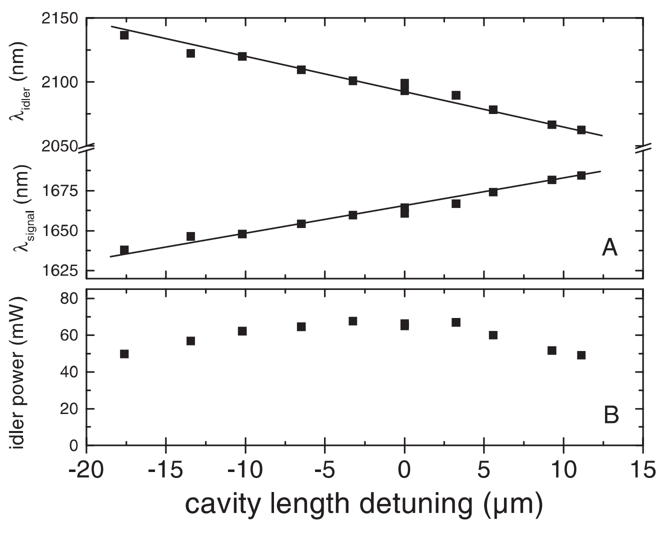

Fig. 4. A Signal and idler wavelengths of the diode-pumped OPO as a function of the cavity-length detuning (straight lines are fitted to data points). The pump wavelength is constant at 927 nm and the pulse-repetition rate of the diode MOPA system is 2.487412 GHz. The PPLN crystal temperature is 151 °C. **B** Idler output power of the OPO as a function of cavity-length detuning. The maximum OPO tuning range is given by the maximum translation of the piezo-transducer

0.5 nm/ms we achieved in this experiment is much higher than the value of typically $R_{S,TEMP} = 0.001$ nm/ms as possible with the commonly applied tuning of the OPO wavelengths via the crystal temperature.

3.2 OPO wavelength tuning via the diode laser repetition rate

A much faster tuning of the OPO was achieved by varying the diode laser repetition rate, while keeping both the cavity length and the crystal temperature constant. Figure 5A shows the measured tuning of the OPO on changing the diode laser repetition rate over ±360 kHz in discrete steps of 20 kHz, where zero detuning corresponds to a repetition rate of 2.487068 GHz. Figure 5A shows that the OPO wavelengths tune in the ranges 1595–1709 nm (signal) and 2215–2026 nm (idler) almost linearly with the repetition rate, with a slope of $d\lambda_S/dF_{REP} = 0.16$ nm/kHz, corresponding to 18 GHz optical tuning per 1 kHz of RF tuning. From (5) we calculate a theoretical slope value of $d\lambda_S/dF_{REP} = 0.158$ nm/kHz, which is in excellent agreement with the experiment.

A comparison of Fig. 4 with 5 shows the first advantage of repetition-rate tuning vs. cavity-length tuning: in our experiment, wavelength tuning through the pump-repetition rate provides a much larger tuning range, because there is no mechanical limit imposed by a physical displacement of the mirror. This can also be seen from Fig. 5B, where the idler output power is shown as a function of the idler wavelength tuned via the repetition rate. Towards both ends of the tuning range the output power decreases gradually to values much below 70% (the value found with piezo-tuning), until the oscillation terminates. At the long-wavelength side, the output power decreases smoothly to zero, which indicates that this tuning limit is given by the width of the parametric amplification profile as described in Sect. 2. We found that the steeper drop of the idler output at the short-wavelength limit was caused by a sharp decrease in the OPO signal cavity finesse. The large signal tuning range of 114 nm measured in the experiment proves a correspondingly large gain bandwidth. Since the OPO was pumped at 2.5 times above the minimum ($\Delta k' = 0$) threshold, the theoretical tuning range can be derived by solving (14) for $\gamma_p = 2.5$. Using the experimental values for the wavelengths and the nonlinear crystal, the theoretical tuning range yields 57 nm, which is in agreement with the experimental value within a factor of two.

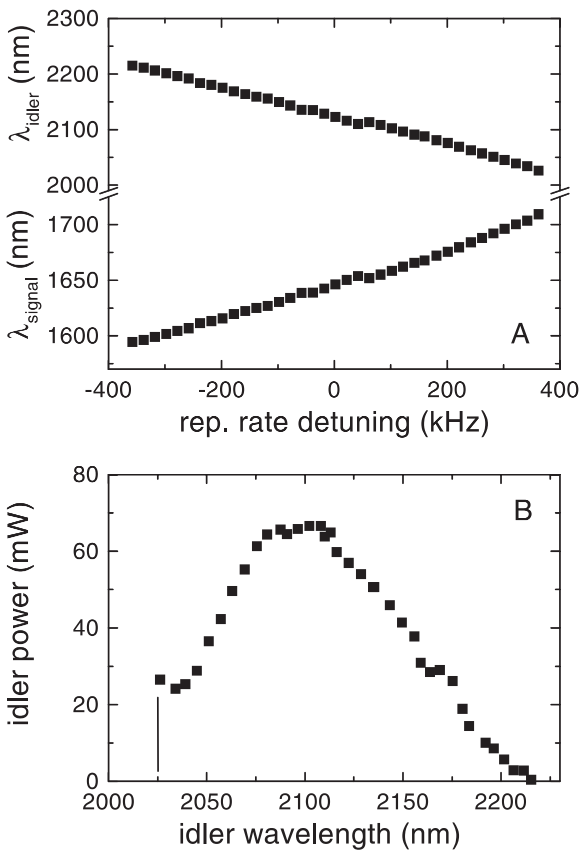

Fig. 5. **A** OPO wavelength tuning as a function of the diode-laser repetition rate. The repetition-rate detuning is relative to a frequency of 2.487068 GHz. **B** Idler output power (one beam) in dependence of the idler wavelength when tuning via repetition rate. The average pump power is 870 mW. The pump wavelength is 927 nm and the crystal temperature 151.5 °C

To test whether a complete spectral coverage of the tuning range in Fig. 5A can be achieved, the repetition rate of the diode laser was tuned continuously over $\Delta F_{REP} = \pm 250$ kHz ($F_{REP} = 2.486480$–2.486980 GHz). This was done by using a sine-shaped modulation function with a period of 100 µs (Fig. 6A) as the input voltage for the voltage-controlled oscillator (VCO) of the RF driver. Figure 6B shows the resulting time-averaged (∼ 1 min) spectrum obtained with an optical spectrum analyser (OSA) set to 0.1 nm resolution. As with the previous measurement, both the crystal temperature (T=155 °C) and the cavity length remained constant. From the smooth trace recorded by the OSA, one can conclude that the OPO generates every signal wavelength in the range 1560 to 1635 nm (within the resolution limit of the OSA), i.e. a complete coverage is observed. For the idler wave this corresponds to a complete coverage ranging from 2140 to 2285 nm.

The shape of the spectrum in Fig. 6B is caused by the power variation of the OPO vs. wavelength as in Fig. 5B, multiplied with the U-shaped duty-cycle function associated with a sine-shaped frequency modulation of the RF driver. The slight deviation of the spectrum from an ideally symmetric spectrum is explained by the fact that the OPO was not operating exactly in the centre of its amplification bandwidth. Note, however, that the shape and symmetry of the time-averaged spectrum can be freely designed, simply by choosing an appropriate modulation function. Such modulation functions are provided, for example, by a programmable waveform generator driving the VCO of the RF generator.

To demonstrate that discrete OPO wavelength outputs with uniform spacings can be produced, we inserted an etalon with a free spectral range of FSR= 660 GHz into the secondary beam waist of the OPO cavity between the mirrors M_3 and M_4. Figure 6C displays the time-averaged spectrum of the OPO equipped with the etalon, when the repetition rate was tuned the same way as in Fig. 6A, however with a somewhat smaller amplitude of the sine function of $\Delta F_{REP} = \pm 140$ kHz. It is observed that the OPO only oscillates on 10 discrete wavelengths with a uniform spacing of 6 nm (660 GHz). This behaviour is explained by the frequency-selective losses of the etalon, which suppress oscillation of the OPO between two ad-

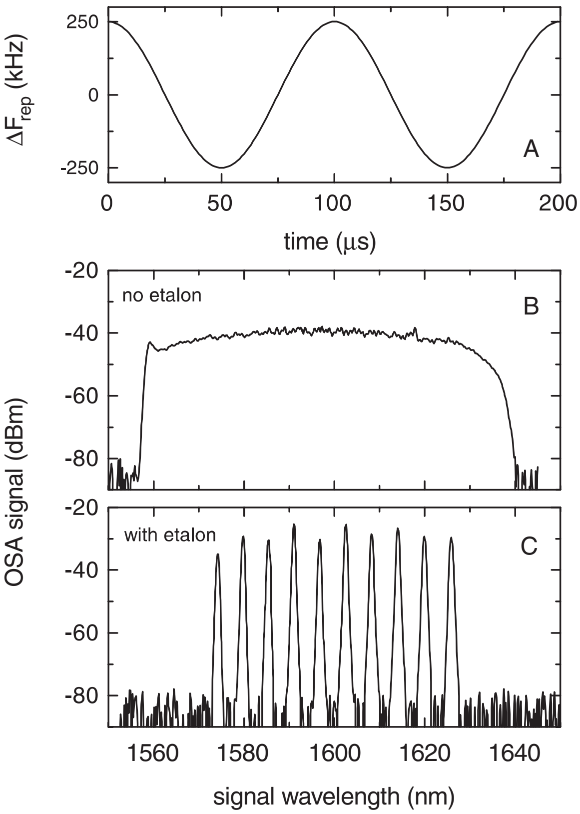

Fig. 6. A Pulse-repetition rate of the diode laser as a function of time, as used for rapid tuning of the OPO wavelengths. **B** Time-averaged signal spectrum of the OPO as measured with the optical spectrum analyser (resolution 0.1 nm) when tuning the OPO through the diode MOPA repetition rate. The average idler power is 75 mW and the tuning range 2.14 to 2.28 μm. **C** Time-averaged signal spectrum of the OPO equipped with an intracavity glass etalon (FSR=660 GHz, corresponding to 6 nm). The average idler power is 11 mW

jacent etalon modes by at least 50 dB in power. Note that in a similar experiment, more than 30 discrete wavelength channels in the range 1628 to 1660 nm (signal, idler: 2153 to 2099 nm) were addressed via repetition-rate tuning, by using an uncoated etalon with a different FSR of 100 GHz (1 nm).

It is interesting to note that the maximum OSA signal is only 40 dBm in Fig. 6B, whereas in Fig. 6C the peaks are as high as 26 dBm, although the average signal power of the OPO is somewhat reduced by transmission losses of the etalon. When tuning the RF manually, we observed that the OPO continues to oscillate on a transmission peak of the etalon, even when a RF value was chosen which corresponds to a signal wavelength between two adjacent peaks. On further tuning the RF, the OPO signal wavelength switched to the next etalon transmission peak. This is because a particular signal wavelength is not only given by the best temporal overlap of the signal pulse with the pump pulse inside the nonlinear crystal, but rather by a compromise of optimum pulse overlap and minimum transmission losses in the etalon. In fact, in our experiment (Fig. 6C), the wavelength selectivity of the intracavity etalon is strong enough to suppress a wavelength shift induced by a change in the temporal pulse overlap due to a tuning of the pump-repetition rate.

3.3 OPO tuning speed and programmable wavelength access

In order to achieve the high spectral resolution of 0.1 nm as displayed in Fig. 6, the OSA time-averages the measurements over one to several minutes. It is clearly seen that the OPO operates only at particular wavelengths, if an intracavity etalon is used. However, these measurements do not show the instantaneous behaviour of the OPO. It is important to determine the actual time span the OPO requires to switch between two different emission wavelengths. For these measurements the OPO cavity was equipped with the etalon, and the crystal temperature was set to 153 °C. The RF repetition rate was switched between two frequencies, 40 kHz apart, such that the OPO signal wavelength switched between two adjacent transmission maxima of the etalon at 1639 and 1645 nm. A diffraction grating (600 lines/mm) was used to spatially separate the two wavelengths, each being deflected onto a different InGaAs photodiode (Hamamatsu PIN G3476-01, cut-off at 100 MHz). Figure 7 shows the traces from the two photodiodes for different switching frequencies, ranging from 2.5 kHz to 500 kHz, as measured with a fast oscilloscope (LeCroy, 100 Msamples/s). In all traces, the 90% rise time of the photodiode signals is about 5 μs when the OPO is switched back and forth between the two selected wavelengths. For moderate switching frequencies below 100 kHz (Fig. 7, traces A and B), both channels can reach their maxima, exhibiting flat tops on the photodiode signals with a maximum on/off contrast of 100%. However, the contrast becomes smaller with increasing switching frequencies (100 kHz: 90%; 200 kHz: 55%; 500 kHz: 40%). The traces C, D, and E indicate a fastest 1/e rise and fall time of 2.5 μs.

It is important to discuss the existence of an upper limit of the switching speed. In our experiment, we found that the switching speed was limited by the RF generator, which required a time interval of about 5 μs for switching by 40 kHz. If this limit is overcome with a faster RF generator, we expect that the maximum speed for OPO wavelength switching will be given by the finite lifetime of signal photons in the OPO cavity. For the current OPO setup with a cold cavity bandwidth of 4 MHz, we thus expect that switching between wavelength channels could be achieved with MHz rates. Nevertheless, let us emphasise that the wavelength tuning rates of $R_S = 1200$ nm/ms we have realised are already about a factor of 2500 faster than possible with piezo-induced OPO tuning, and more than 10^6 times faster than possible with conventional tuning via the crystal temperature.

To demonstrate that the fast wavelength switching of the OPO is not limited to periodic switching of the RF generator, we drove the RF signal generator with a quasi-random signal from a programmable waveform generator (Stanford Research DS345). As an example, we deliberately chose a sequence consisting of the letters "SPSRO" in ASCII notation as shown in Fig. 8A. The length of the sequence is 400 μs, such that the shortest dwelling time on one repetition rate ("1 bit") corresponds to the shortest switch time of the RF driver of 10 μs (rise + fall time), as observed before. The two repetition rates produced by the RF generator correspond to OPO signal wavelengths of 1633.5 nm and 1639.5 nm, respectively. A third repetition rate corresponding to a signal wavelength of 1645.5 nm was programmed at the beginning of each sequence to serve as the trigger signal. Figure 8B and C show the variation of the relative power vs. time at the first two signal wavelengths, which was monitored as described before. A comparison of trace A with traces B and C shows that the OPO signal wavelength follows the input bit sequence with high fidelity, even at the highest rates of 10 μs/channel. Additional information on the fidelity of this wavelength switching is obtained from the time-averaged spectrum. Figure 9 shows the OPO signal spectrum averaged over 2 min (∼300 000 cycles of the switching sequence), as measured with the OSA, set to a resolution of 0.1 nm. It is observed that the spectral power density belonging to wavelengths other than the ones used for encoding the sequence is suppressed by more than 30 dB.

We note that a programmable and rapid wavelength access is not restricted to two wavelengths as shown in Figs. 7 and 8, but can involve a large number of discrete wavelengths within the signal wave amplification bandwidth of the crystal. For example, we programmed a step function of 11 repetition rates, with a dwelling time of 10 μs on each step. By this, 11 wavelength channels were addressed, which were equidistantly spaced by 660 GHz in the ranges 1627 to 1689 nm and 2154 nm to 2054 nm, for the signal wave and for the idler wave, respectively. With improved frequency-modulation techniques and multi-channel time-resolved analysis of the OPO spectra, it should be possible to demonstrate multi-channel operation at even higher wavelength switching rates, which can theoretically be as short as the OPO cavity lifetime of considerably less than 1 μs.

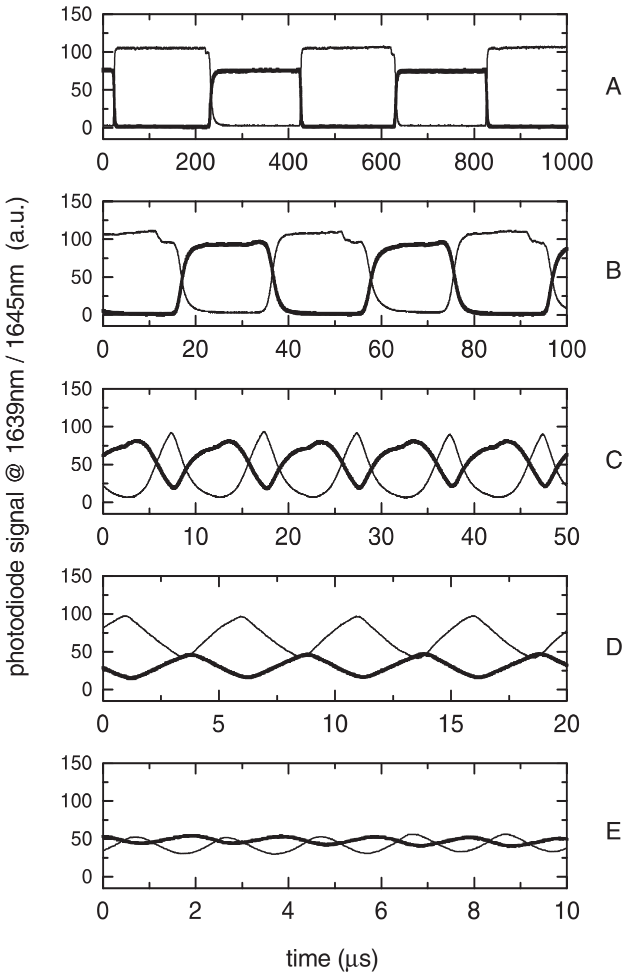

Fig. 7. OPO signal power at 1639 nm (*thin lines*) and 1645 nm (*thick lines*) on rapidly switching the pump-repetition rate between two values. Switching rates: A 2.5 kHz; B 25 kHz; C 100 kHz; D 200 kHz; E 500 kHz. The two OPO signal wavelengths are separated with a grating and monitored simultaneously with InGaAs photodiodes. For switching rates higher than 100 kHz, the maximum power and the contrast of the two signals is reduced because of the limited modulation speed of the repetition rate imposed by the RF generator

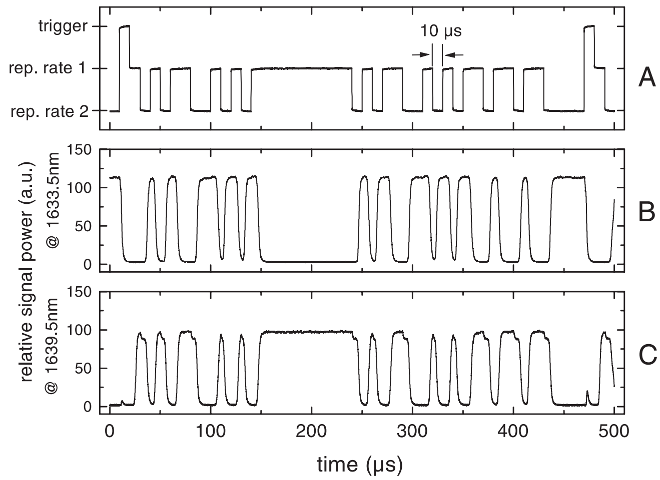

Fig. 8. Rapid programmable wavelength access demonstrated by switching the OPO repetition rate between two values in an arbitrary sequence. A 400 μs long switching sequence from the programmable function generator driving the pump-repetition rate, with a shortest dwelling time of 10 μs on any repetition rate. B, C signal output powers of the OPO at 1634 nm (B, "signal 1") and 1640 nm (C, "signal 2"), spectrally analysed with a grating and monitored with two separate InGaAs photodiodes

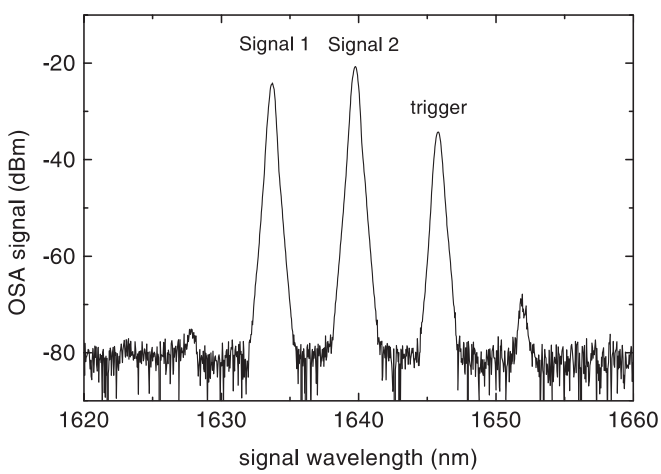

Fig. 9. OPO signal spectrum averaged over 300 000 cycles of the 400 μs-long arbitrary switching sequence of the pump-laser repetition rate. The major peaks, labelled 'signal 1' and 'signal 2', correspond to the two repetition rates the RF generator is switched to in the sequence. The third peak, 'trigger', corresponds to the repetition rate used as ∼ 10 μs-long trigger signal once per cycle. Other peaks are suppressed by more than 30 dB

4 Summary and conclusions

In summary, we have investigated rapid wavelength tuning and programmable wavelength access with a diode-laser synchronously pumped OPO based on QPM material. We theoretically analysed how to maximise the OPO tuning range and tuning speed. We find that the largest tuning range and the highest tuning speed are obtained by using a diode-pump laser with an electronically adjustable RF driver to tune the OPO via the diode-laser repetition rate, rather than by tuning the OPO wavelength via its cavity length. Further calculations show that a wide gain bandwidth at any desired signal or idler wavelength and thus a wide OPO tuning range can be achieved by an appropriate choice of the pump wavelength and the nonlinear material.

These predictions are verified by experiments with a picosecond OPO based on PPLN, which is directly pumped by a 927 nm CW actively mode-locked diode-laser system with its repetition rate electronically tunable near 2.5 GHz. The singly (signal) resonant OPO had a minimum average pump power at threshold of 300 mW. Wavelength tuning from 1600 to 1660 nm (signal) and 2100 to 2200 nm (idler) with a moderate signal wave tuning rate of up to $R_S = 0.5$ nm/ms was achieved by changing the OPO cavity length with a piezo-transducer.

Much wider and faster tuning of the OPO was demonstrated by electronically changing the repetition rate of the diode-laser pump pulses. By tuning the repetition rate over ±360 kHz, the OPO was tuned from 1595 to 1709 nm (signal) and from 2215 to 2026 nm (idler), in excellent agreement with theory. Rapid wavelength coverage of an interval of 75 nm (signal, idler: 145 nm) was achieved by modulating the RF-driver frequency with a sine function. The maximum signal wavelength tuning rate was 1500 nm/ms, which corresponds to a frequency tuning rate of 176 THz/ms. On continuous variation of the repetition rate, the OPO was forced to tune in discrete steps by using an intracavity etalon with a free spectral range of 660 GHz (6 nm). Rapid, periodic switching between two signal wavelengths spaced 6 nm was demonstrated by modulating the RF frequency with a rectangular function, and by time-resolved monitoring of the spectrally resolved OPO signal. Switching with near 100% contrast of the two signal wavelengths was possible at switching rates of up to 100 kHz. Higher rates of up to 200 kHz were demonstrated with 50% contrast. Programmable, aperiodic rapid access to two different OPO wavelength channels was demonstrated by modulating the repetition rate with a pre-programmed switching sequence. A contrast of 100% was observed for a shortest dwelling time of 10 µs per channel. Rapid switching across 11 different wavelengths (spaced 6 nm) was achieved by driving the pump-repetition rate with a step function with a duration of 10 µs per step.

In conclusion, we have demonstrated that rapid, all-electronically controlled wavelength access via changing the pump-laser repetition rate is a unique feature gained by pumping OPOs synchronously with a mode-locked diode-laser system. Using different QPM materials and pump wavelengths, this concept is expected to work within the entire transparency range of QPM nonlinear materials in the near and mid infrared. With these interesting properties, potential applications might include the characterisation of telecommunications devices, and high-speed acquisition of spectroscopic data for monitoring chemical processes and product quality.

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