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Authors: Sukeert .,Sara Pizzurro,Adolfo Esteban Martín,Riccardo Gotti,Luca Carrà,Giuliano Piccinno,Antonio Agnesi,Federico Pirzio,Chaitanya Kumar Suddapalli,Majid Ebrahim-Zadeh

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Efficient femtosecond optical parametric generation in group-velocity-matched MgO:PPLN at 10 MHz

SUKEERT,[1†*] S. PIZZURRO,[2†] A. ESTEBAN-MARTÍN,[3] R. GOTTI,[2] L. CARRÀ,[4] G. PICCINNO,[4] A. AGNESI,[2] F. PIRZIO,[2] S. CHAITANYA KUMAR,[5] AND M. EBRAHIM-ZADEH[1,6]

[1]*ICFO—Institut de Ciències Fotòniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain*
[2]*Dipartimento di Ingegneria Industriale e dell'Informazione, Università di Pavia, Via Ferrata 5, 27100 Pavia, Italy*
[3]*Departament d'Òptica i Optometria i Ciències de la Visió, Universitat de València, Dr. Moliner 50, 46100-Burjassot, Spain*
[4]*Bright Solutions Srl, Via degli Artigiani 27, 27010 Cura Carpignano (PV), Italy*
[5]*Tata Institute of Fundamental Research Hyderabad, 36/P Gopanpally, Hyderabad 500046, Telangana, India*
[6]*Institució Catalana de Recerca i Estudis Avançats (ICREA), Passeig Lluís Companys 23, Barcelona 08010, Spain*
[†] *These authors contributed equally*
**Corresponding author: sukeert@icfo.eu*

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We report on efficient single-pass optical parametric generation (OPG) of broadband femtosecond pulses in the mid-infrared at 10 MHz by exploiting group-velocity-matched interaction in a 42-mm-long MgO:PPLN crystal. Using a microchip-started femtosecond amplified Mamyshev oscillator at 1064 nm as the pump, the OPG source can provide tunable femtosecond pulses across 1516-1566 nm in the signal and 3318-3568 nm in the idler, with slope efficiencies of ~93% and ~41%, respectively. For 650 mW of average input pump power, signal powers up to 283 mW at 1524 nm are generated, with more than 200 mW over the entire tuning range. Idler average powers up to 104 mW at 3450 nm, with more than 80 mW across the full range are also obtained. For input pump pulses of ~182 fs, the generated signal pulses have a duration of ~460 fs at 1516 nm. The idler pulses have typical bandwidth ≥100 nm over the entire tuning range, and as wide as 181 nm at 3457 nm. The OPG source exhibits excellent passive power stability, better than 0.5% rms in the signal and 0.6% rms in the idler, over 1 hour, both in Gaussian TEM_{00} spatial profile with M^2<1.5.

Femtosecond laser sources in the near- and mid-infrared are of great interest for a variety of applications including spectroscopy, frequency comb generation, material processing, laser surgery [1,2]. Nonlinear frequency conversion devices, in particular synchronously-pumped optical parametric oscillators (OPOs), are now well established as viable and practical sources of kW-level femtosecond pulses at high repetition rate (~80-100 MHz) from the visible to mid-infrared [3–5]. Such ultrafast OPOs require complex design and precise temporal synchronization between the pump and generated pulses in the resonant cavity. For some applications, such as multiphoton microscopy, femtosecond pulses at higher energies and lower repetition rates (few MHz) are favorable [6]. Moreover, a lower repetition rate enables maintaining high pulse energies at low average powers, thus mitigating the damage caused due to high average power, which is crucial for diagnostic applications. At such low pulse repetition rates, the requirement for synchronous pumping results in very long cavities, making OPOs impractical for femtosecond pulse generation. In this regime, single-pass optical parametric generation (OPG) is the most effective approach for down-conversion of femtosecond pump pulses into the near- and mid-infrared, also offering far greater simplicity by eliminating the need for a resonant cavity. The low repetition rate also enables generation of high pulse energies at low average pump powers. At the same time, the nature of single-pass interaction in the OPG process necessitates the use of high pulse pump intensities over sufficiently long interaction length for the attainment of practical conversion efficiencies. In the femtosecond regime, however, the interaction length is generally limited by group-velocity-mismatch (GVM) among the pump, signal and idler pulses, as they propagate with different group velocities through the nonlinear crystal. The GVM also results in narrow pump spectral acceptance bandwidth for long crystals (Δλ<1 nm), which is well below the typical bandwidth of a femtosecond laser, hence severely limiting parametric gain. As such, the development of femtosecond OPG sources mandates the use of short crystal interaction lengths (~1-2 mm) to accommodate the pump bandwidth for the attainment of practical conversion efficiencies. On the other hand, under certain conditions, the dispersion properties of the nonlinear crystal can result in equal group velocities of the pump and generated waves, such that the GVM is close to zero at wavelengths satisfying phase-matching. In this case, the pump spectral acceptance bandwidth is not strongly dependent on the crystal length, thus relaxing the restriction on the interaction length to accommodate the pump bandwidth [7]. For example, in MgO-doped periodically-poled $LiNbO_3$ (MgO:PPLN), using the Sellmeier equations for the material [8], at the pump wavelength of 1064 nm and for a crystal length of 42 mm, the calculated pump acceptance bandwidth is <1 nm at the signal wavelength of 1400 nm, whereas

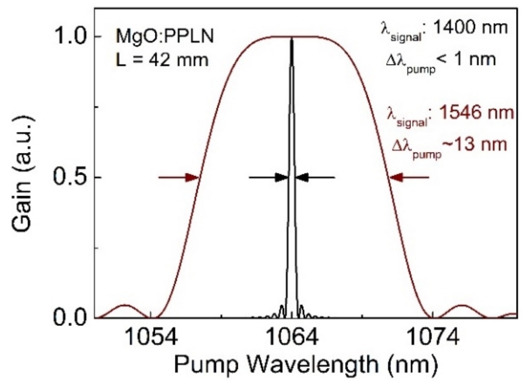

Fig. 1. Pump acceptance bandwidth for signal wavelength away from GVM (black line) and close to zero GVM (red line) for a 42-mm-long MgO:PPLN crystal.

at the signal wavelength of 1546 nm close to zero-GVM, the pump acceptance bandwidth increases to ~13 nm, as shown in Fig. 1. In such a case, the pump bandwidth is transferred primarily to the idler, thus providing broadband idler output [9]. The concept of GVM-matched interaction has been previously investigated in a number of configurations in parametric devices based on MgO:PPLN. We exploited this technique in a continuous-wave OPO for efficient conversion of broadband pump radiation to mid-infrared idler output [7]. Subsequently, the concept was deployed in a femtosecond OPO operating at 94 MHz repetition rate [10], in femtosecond OPG at 78 MHz repetition rate [11], and in a later report we demonstrated a femtosecond OPO at 80 MHz based on this approach [9]. In this letter, we report an efficient broadband femtosecond OPG source at 10 MHz pulse repetition rate based on GVM-matched MgO:PPLN. Our OPG source is based on a microchip-started amplified Mamyshev oscillator as the pump source, and a 42-mm-long crystal as the gain medium. Pumping at 1064 nm, the source can deliver near-infrared signal pulses across 1516-1566 nm and broadband idler output over 3318-3568 nm. The combination of the amplified Mamyshev oscillator providing pulse energies of 65 nJ at 10 MHz and GVM-matched interaction in a 42-mm-long crystal results in record conversion efficiency and output power. The source can provide as much as 283 mW of average power in the signal and up to 104 mW in the idler with excellent power stability, in Gaussian spatial profile, with an idler bandwidth as broad as 181 nm at 3457 nm. To the best of our knowledge, this is the first report on femtosecond OPG at 10 MHz repetition rate and

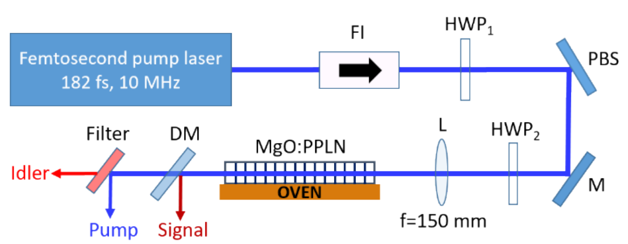

Fig. 2. Schematic of the experimental setup for femtosecond GVM-matched OPG source based on MgO:PPLN. Femtosecond pump laser: microchip-started femtosecond amplified Mamyshev oscillator; FI: Faraday isolator; HWP: half-wave-plate; PBS: polarizing beam-splitter; L: lens; DM: dichroic mirror.

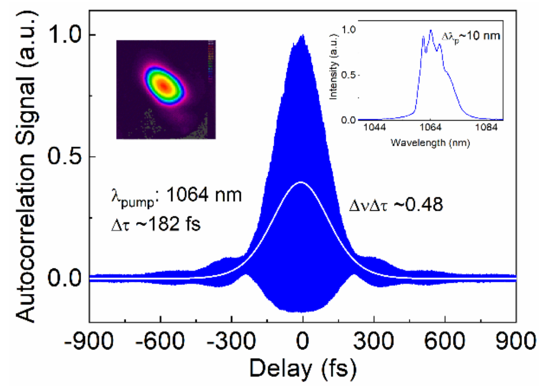

Fig. 3. Autocorrelation trace of the output pulse from the Mamyshev oscillator/amplifier. Inset: (left) spatial beam profile, and (right) spectrum.

the first use of a Mamyshev oscillator for OPG/OPO in MgO:PPLN.

The schematic of the experimental setup of our GVM-matched OPG source is shown in Fig. 2. The output of a home-built Mamyshev fiber oscillator [12], providing 40 mW of average power in 2 ps pulses at 10 MHz repetition rate, is amplified using an Yb-fiber amplifier. The output pulses from the amplifier are subsequently compressed using a Treacy pulse compressor scheme with four-bounce single grating, resulting in ~182 fs pulses, as shown in Fig. 3. The pulses are at ~10 MHz repetition rate, centered at 1064 nm with full-width at half-maximum (FWHM) bandwidth of ~10 nm, as shown in the inset of Fig. 3, which is well within the pump acceptance bandwidth of ~13 nm for the 42-mm-long MgO:PPLN gain crystal shown in Fig. 1. A Faraday isolator (FI) is placed in the beam path to avoid back-reflection into the Mamyshev oscillator, and a combination of half-wave-plate (HWP_1) and polarizing beam-splitter (PBS) is used to attenuate the input power, while a second half-wave plate (HWP_2) is used to control the pump polarization. Using a lens (L) of focal length, f=150 mm, the pump beam is focused to a waist radius of w_0~60 µm. The 5 mol% MgO:PPLN crystal is 42-mm-long , 2-mm-wide, and 1-mm-thick, with seven uniform gratings ranging in period from Λ=28.5 µm to Λ=31.5 µm, in steps of 0.5 µm, designed for type-0 *(e→ee)* quasi-phase-matched (QPM) interaction. The end faces of the crystal are antireflection-coated at 1064 nm (R<1%), 1400-2000 nm (R<0.5%), and 2000-4000 nm (R<7%). The crystal is housed in an oven with a stability of ±0.1 °C to control the phase-matching temperature and mounted on a translation stage. A combination of a dichroic mirror and a long-pass filter is used to separate the OPG output from the residual pump after collimation.

For the pump wavelength centered at 1064 nm, using relevant Sellmeier equations of the material [8], the theoretically calculated idler wavelength for near-zero GVM in MgO:PPLN requires a grating period of Λ=30 µm, with the central wavelength of the idler varying from 3390 nm to 3422 nm for a corresponding phase-matching temperature of 40 °C to 200 °C. Therefore, the crystal grating period of Λ=30 µm was used for this experiment. For a fixed average pump power of 650 mW, by varying the crystal temperature from 40 °C to 200 °C, we were able to tune the OPG output across 1516-1566 nm in the signal, and 3318-3568 nm in the idler, with the results shown in Fig. 4. The dots correspond to experimentally measured data while the solid lines are theoretical curves from the Sellmeier equations for MgO:PPLN [8]. The signal

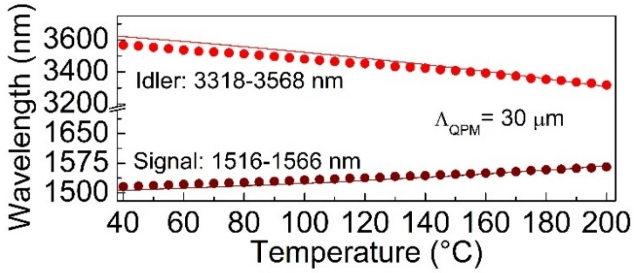

Fig. 4. Signal and idler wavelength tuning range of the femtosecond GVM-matched OPG source.

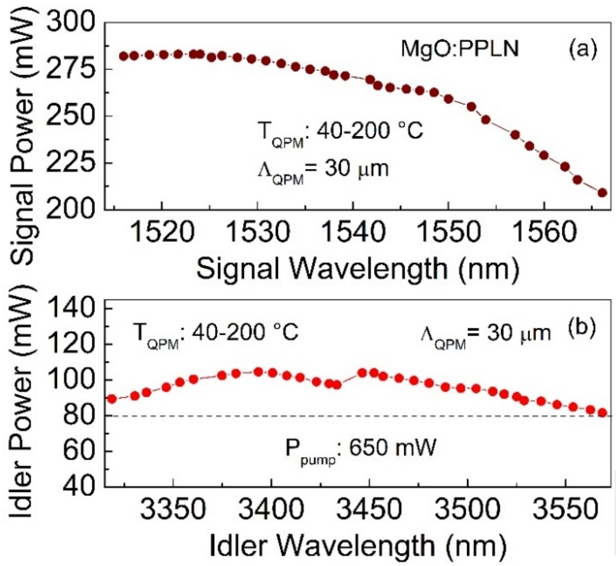

Fig. 5. (a) Signal, and (b) idler average power across the tuning range of femtosecond GVM-matched OPG source.

wavelengths were measured using a spectrometer (Radiantis Seawave, resolution ~3 nm) and the idler wavelengths were measured using a mid-IR wavemeter (Bristol 721). The discrepancy between the measured wavelengths and theoretical curves (where an exact pump wavelength of 1064 nm is assumed) could be due non ideal pump spectrum, as shown in Fig. 2, as well as the difference in the actual crystal temperature and set temperature of the oven. We performed measurements of output power where we recorded the signal average power varying from 282 mW at 1516 nm to 209 mW at 1566 nm, with a maximum of 283 mW at 1524 nm, thus providing more than 200 mW of average power over the signal tuning range, as shown in Fig. 5(a). The idler average power varied from 89 mW at 3319 nm to 82 mW at 3569 nm, with a maximum of 104 mW at 3450 nm, thus providing more than 80 mW of average power over the entire tuning range, as shown in Fig. 5(b). The minimal change in the idler power across the tuning range could be attributed to the near-zero GVM between the pump and idler in the group-velocity-matched configuration. It should be noted that the powers are not corrected for transmission losses of the dichroic mirror and the long-pass filter, which amount to a total of ~5%. Hence, the maximum average power generated from the source is as much as ~300 mW in the signal and ~110 mW in the idler. Typical signal spectra across the tuning range are shown in Fig. 6(a). The spectra have typical bandwidth of ~10 nm. We also

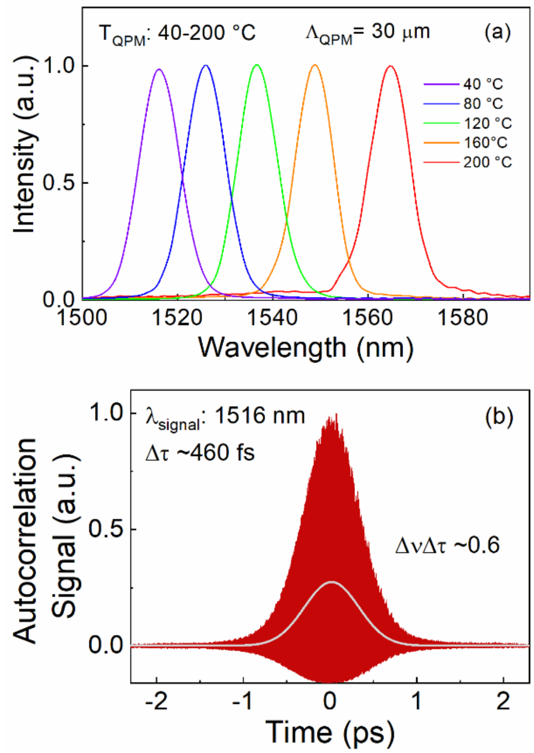

Fig. 6. (a) Signal spectra across the tuning range of the femtosecond GVM-matched OPG source, and (b) autocorrelation trace of the signal at 1516 nm.

measured the signal pulse duration using interferometric autocorrelation, resulting in a duration of ~460 fs at 1516 nm (assuming a Gaussian pulse shape), as shown in Fig. 6(b). The corresponding time-bandwidth product is estimated to be $\Delta\tau\Delta\nu$~0.6. The measured idler spectra across the tuning range are shown in Fig. 7. The idler has a typical bandwidth of ≥100 nm across the tuning range, with a maximum of ~181 nm at 3457 nm. At a fixed oven temperature of 130 °C, we also studied the variation of output power as a function of input pump power at signal and idler wavelengths of 1540 and 3442 nm, respectively, with the results shown in Fig. 8. The OPG threshold pump power was 180 mW. As

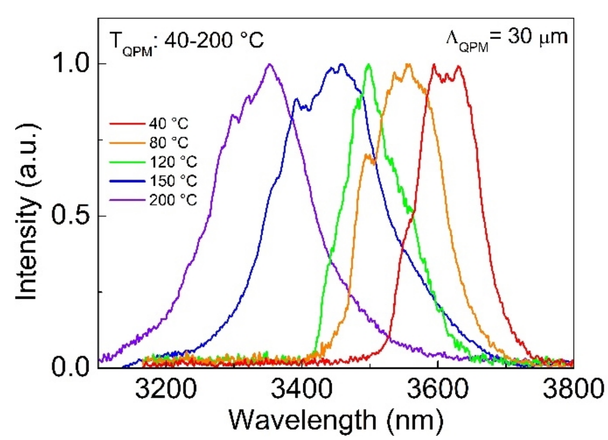

Fig. 7. Idler spectra across the tuning range of femtosecond GVM-matched OPG source.

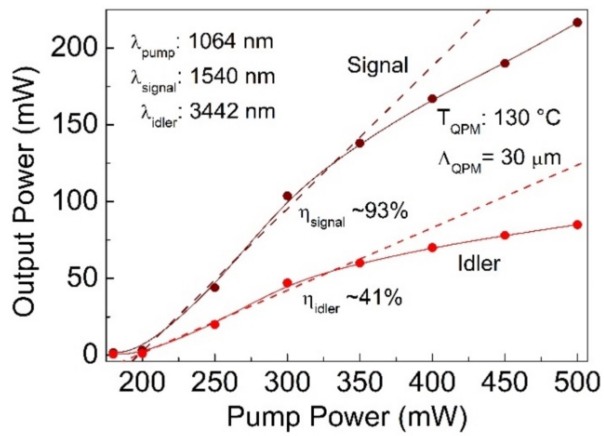

Fig. 8. Signal and idler average power scaling of the femtosecond GVM-matched OPG source.

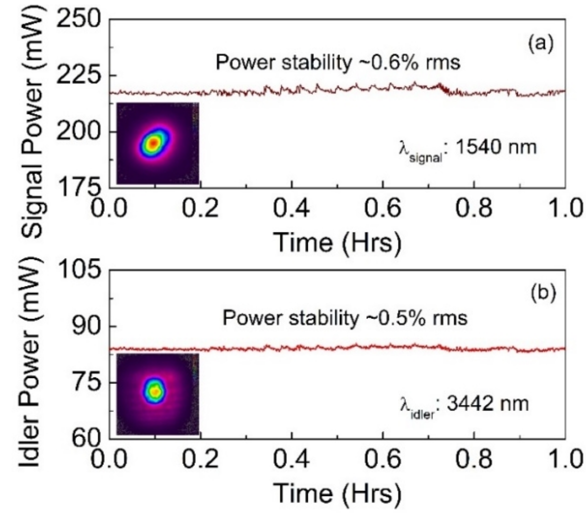

Fig. 9. Passive power stability of (a) signal, and (b) idler over 1 hour. Inset: Corresponding spatial beam profile.

evident from the plot, both the signal and idler average power scale linearly with pump power up to 350 mW at slope efficiency of ~93% and ~41%, respectively. At higher pump powers, we observe the onset of saturation. For 500 mW of pump power, the OPG source could provide 217 mW of signal power, corresponding to a conversion efficiency of 43.4%, and 85 mW of idler power, representing a conversion efficiency of 17%. The total output conversion efficiency is more than 60%. Again, it should be noted that the measured output powers do not account for the ~5% transmission loss of the dichroic mirror and the long-pass filter. The simultaneously recorded passive power stability of the OPG output at 500 mW of input pump power, recorded at signal and idler wavelengths of 1540 nm and 3442 nm, together with the corresponding spatial beam profiles, are shown in Fig. 9(a) and 9(b), respectively. As can be seen, the signal exhibits a power stability better than 0.6% rms over 1 hour, while the idler displays a power stability better than 0.5% rms over the same period. The pump power stability was measured to be 0.4% rms over 1 hour. Both signal and idler beams have Gaussian TEM_{00} spatial distribution, with similar profiles recorded across the entire OPG tuning range. Characterization of the beam quality resulted in a measured value of M^2 <1.5 for both the signal and idler beams.

In conclusion, we have demonstrated efficient generation of femtosecond near-IR and broadband mid-IR pulses at 10 MHz repetition rate based on simple single-pass OPG in MgO:PPLN, for the first time. Pumped by a microchip-started amplified Mamyshev oscillator and exploiting GVM-matched interaction in 42-mm-long crystal, we have generated up to 283 mW of signal average power and 104 mW of idler average power for 650 mW of pump power, with broadband (≥100 nm) idler spectra, high conversion efficiencies, with excellent power stabilities in Gaussian TEM_{00} beam profiles. The repetition rate of 10 MHz results in a low threshold for the single-pass OPG process, ensuring further power scalability, also enabling the extension of the tuning range by using alternative grating periods. The practical output powers, high conversion efficiency, and broad spectral bandwidths, together with high spectral and spatial beam quality at 10 MHz repetition rate make the Mamyshev-pumped OPG source attractive for access to near- to mid-IR femtosecond pulses at relatively high energy at low average power, benefiting various applications including multiphoton microscopy, broadband spectroscopy, and more.

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Disclosures. The authors declare no conflicts of interest.

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