List of Publications using Covesion PPLN

version 4.1/2016

SHG OPO/OPA DFG SFG OPG/SPDC

Optical Communications, vol. 370, pp. 150–155, (2016)
Realization and characterization of single-frequency tunable 637.2 nm high-power laser
J. Wang, J. Bai, J. He, and J. Wang
We report the preparation of narrow-linewidth 637.2 nm laser device by single-pass sum-frequency generation (SFG) of two infrared lasers at 1560.5 nm and 1076.9 nm in PPMgO:LN crystal. Over 8.75 W of single-frequency continuously tunable 637.2 nm laser is realized, and corresponding optical-optical conversion efficiency is 38.0%. We study the behavior of crystals with different poling periods. The detailed experiments show that the output red lasers have very good power stability and beam quality. This high-performance 637.2 nm laser is significant for the realization of high power ultra-violet (UV) 318.6 nm laser via cavity-enhanced frequency doubling. Narrow-linewidth 318.6 nm laser is important for Rydberg excitation of cesium atoms via single-photon transition.

Mid Infrared Coherent Sources (2016), MT2C.2
Multi-Watt-level 3.28-3.45 um difference frequency generation using synchronous fiber lasers
R.T. Murray, E. J. R. Kelleher, T. Runcorn, and J. R. Taylor
We report multi-Watt-level average power 3.28-3.45 µm difference frequency generation using two sychronous picosecond master oscillator power fiber amplifiers. Greater than 3.4 W of idler power is generated across the entire spectral tuning range.

Optics Express, vol. 24, no. 4, p. 4117, (2016)
2D IR spectroscopy at 100 kHz utilizing a Mid-IR OPCPA laser source
B. M. Luther, K. M. Tracy, M. Gerrity, S. Brown, and A. T. Krummel
We present a 100 kHz 2D IR spectrometer. The system utilizes a ytterbium all normal dispersion fiber oscillator as a common source for the pump and seed beams of a MgO:PPLN OPCPA. The 1030 nm OPCPA pump is generated by amplification of the oscillator in cryocooled Yb:YAG amplifiers, while the 1.68 µm seed is generated in a OPO pumped by the oscillator. The OPCPA outputs are used in a ZGP DFG stage to generate 4.65 µm pulses. A mid-IR pulse shaper delivers pulse pairs to a 2D IR spectrometer allowing for data collection at 100 kHz.

arXiv Prepr. arXiv1610.04359, (2016)
Experimental demonstration of high-dimensional photonic spatial entanglement between multi-core optical fibers
H. Lee, S. Choi, and H. Park
Fiber transport of multi-dimensional photonic qudits promises high information capacity per photon without space restriction. This work experimentally demonstrates transmission of spatial qudits through multi-core optical fibers and measurement of the entanglement between two fibers with quantum state analyzers, each composed of a spatial light modulator and a single-mode fiber. Quantum state tomography reconstructs the four-dimension entangled state that verifies the non-locality through concurrences in two-dimensional subspaces and a high-dimensional Bell-type CGLMP inequality.

Photonics and Fiber Technology 2016 (ACOFT, BGPP, NP), 2016, p. AW2B.2.
Second Harmonic Generation Using a Monolithic, Linearly Polarized Thulium Doped Fiber Laser
M. Ganija, N. Simakov, A. Hemming, et al.
We investigate the potential for power scaling of 975 nm cw radiation from frequency doubling a monolithic, polarized thulium fiber laser in a periodically poled non-linear material.

arXiv Prepr. arXiv1608.08013 , (2016)
Mid-infrared dual-comb spectroscopy with electro-optic modulators
M. Yan, P. Luo, K. Iwakuni, G. Millot, and T. Hänsch
We demonstrate dual-comb spectroscopy based on difference frequency generation of frequency-agile near-infrared frequency combs, produced with the help of electro-optic modulators. The combs have a remarkably flat intensity distribution and their positions and line spacings can be selected freely by simply dialing a knob. We record, in the 3-micron region, Doppler-limited absorption spectra with resolved comb lines within milliseconds. Precise molecular line parameters are retrieved. Our technique holds promise for fast and sensitive time-resolved studies e.g. of trace gases.

Optics Express, vol. 24, no. 18, p. 20245, (2016)
Nonlinear ptychographic coherent diffractive imaging
M. Odstrcil, P. Baksh, C. Gawith, R. Vrcelj, J. G. Frey, and W. S. Brocklesby

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Ptychographic Coherent diffractive imaging (PCDI) is a significant advance in imaging allowing the measurement of the full electric field at a sample without use of any imaging optics. So far it has been confined solely to imaging of linear optical responses. In this paper we show that because of the coherence-preserving nature of nonlinear optical interactions, PCDI can be generalised to nonlinear optical imaging. We demonstrate second harmonic generation PCDI, directly revealing phase information about the nonlinear coefficients, and showing the general applicability of PCDI to nonlinear interactions.

Lasers Congress 2016 (ASSL, LSC, LAC), 2016, p. AW1A.3
Mid-Infrared Difference Frequency-Generation with Synchronized Fiber Lasers
R. T. Murray, T. H. Runcorn, E. J. R. Kelleher, S. Guha, and J. R. Taylor
We present results on high-average power difference frequency generation of pulsed Yb/Er fiber systems to the mid-IR (6.2 W at 3.35 µm), and use focused Gaussian beam theory to validate our experimental results.

Conference on Lasers and Electro-Optics, 2016, p. SM2Q.4
Synchronized dual-repetition-rate two-color fiber lasers for coherent Raman imaging
C. Kong, X. Wei, T. Huser, K. K. Tsia, and K. K. Y. Wong
We demonstrate a passively synchronized two-color pulsed fiber laser with dual repetition rates, 20 MHz for 1.0 mm and 80 MHz for 782 nm. The wavelength tunability of both synchronized pulse sources is also investigated.

Lasers Congress 2016 (ASSL, LSC, LAC), 2016, p. ATu1A.1
First Detection and Stabilization of the Carrier Envelope Offset of a Diode-Pumped Mode-Locked Ti : Sapphire Laser
K. Gürel, V. J. Wittwer, S. Hakobyan, S. Schilt, and T. Südmeyer
So far, Ti:Sapphire-based frequency comb systems required complex bulk green pump lasers. Here we show that green diode pumping enables compact and cost-efficient femtosecond Ti:Sapphire lasers for coherent octave-spanning supercontinuum generation and frequency comb stabilization.

Scientific Reports, vol. 6, p. 21390, (2016)
Frequency conversion of structured light
F. Steinlechner, N. Hermosa, V. Pruneri, and J. P. Torres
Coherent frequency conversion of structured light, i.e. the ability to manipulate the carrier frequency of a wave front without distorting its spatial phase and intensity profile, provides the opportunity for numerous novel applications in photonic technology and fundamental science. In particular, frequency conversion of spatial modes carrying orbital angular momentum can be exploited in sub-wavelength resolution nano-optics and coherent imaging at a wavelength different from that used to illuminate an object. Moreover, coherent frequency conversion will be crucial for interfacing information stored in the high-dimensional spatial structure of single and entangled photons with various constituents of quantum networks. In this work, we demonstrate frequency conversion of structured light from the near infrared (803 nm) to the visible (527 nm). The conversion scheme is based on sum-frequency generation in a periodically poled lithium niobate crystal pumped with a 1540-nm Gaussian beam. We observe frequency-converted fields that exhibit a high degree of similarity with the input field and verify the coherence of the frequency-conversion process via mode projection measurements with a phase mask and a single-mode fiber. Our results demonstrate the suitability of exploiting the technique for applications in quantum information processing and coherent imaging.

Applied Physics B, vol. 122, no. 5, p.122, (2016)
A simple 2 W continuous-wave laser system for trapping ultracold metastable helium atoms at the 319.8 nm magic wavelength
LR. J. Rengelink, R. P. M. J. W. Notermans, and W. Vassen
High-precision spectroscopy on the 2 3S→2 1S transition is possible in ultracold optically trapped helium, but the accuracy is limited by the ac-Stark shift induced by the optical dipole trap. To overcome this problem, we have built a trapping laser system at the predicted magic wavelength of 319.8 nm. Our system is based on frequency conversion using commercially available components and produces over 2 W of power at this wavelength. With this system, we show trapping of ultracold atoms, both thermal (~0.2 µk) and in a Bose–Einstein condensate, with a trap lifetime of several seconds, mainly limited by off-resonant scattering.

Optics Express, vol. 24, no. 17, p. 19558, (2016)
Narrowband cw injection seeded high power femtosecond double-pass optical parametric generator at 43 MHz: Gain and noise dynamics
H. Linnenbank, T. Steinle, and H. Giessen

We demonstrate narrowband cw injection seeding of a femtosecond double-pass optical parametric generator at 43 MHz repetition rate with a simple, low power external cavity diode laser. Up to 2.5 W of near-IR radiation (1.5 – 1.66 µm) as well as 800 mW of tunable mid-IR radiation (2.75 – 3.15 µm) with pulse durations below 300 fs are generated with a remarkable pulse-to-pulse and long term power stability. Compared to conventional, vacuum noise seeded optical parametric generators, the presented frequency conversion scheme does not only exhibit superior gain and noise dynamics, but also a high degree of flexibility upon control parameters such as pump power, seed power, or spectral position of the seed.

Biomed. Opt. Express, vol. 7, no. 5, p. 1948, (2016)

Miniature fiber-optic multiphoton microscopy system using frequency-doubled femtosecond Er-doped fiber laser

L. Huang, A. K. Mills, Y. Zhao, D. J. Jones, and S. Tang

We report on a miniature fiber-optic multiphoton microscopy (MPM) system based on a frequency-doubled femtosecond Er-doped fiber laser. The femtosecond pulses from the laser source are delivered to the miniature fiber-optic probe at 1.58 µm wavelength, where a standard single mode fiber is used for delivery without the need of free-space dispersion compensation components. The beam is frequency-doubled inside the probe by a periodically poled MgO:LiNbO3 crystal. Frequency-doubled pulses at 786 nm with a maximum power of 80 mW and a pulsewidth of 150 fs are obtained and applied to excite intrinsic signals from tissues. A MEMS scanner, a miniature objective, and a multimode collection fiber are further used to make the probe compact. The miniature fiber-optic MPM system is highly portable and robust. Ex vivo multiphoton imaging of mammalian skins demonstrates the capability of the system in imaging biological tissues. The results show that the miniature fiber-optic MPM system using frequency-doubled femtosecond fiber laser can potentially bring the MPM imaging for clinical applications.

Optics Express, vol. 24, no. 5, p. 5152, (2016)

Upconversion-based lidar measurements of atmospheric CO_2

L. Høgstedt, A. Fix, M. Wirth, C. Pedersen, and P. Tidemand-Lichtenberg

For the first time an upconversion based detection scheme is demonstrated for lidar measurements of atmospheric CO2-concentrations, with a hard target at a range of 3 km and atmospheric backscatter from a range of ~450 m. The pulsed signals at 1572 nm are upconverted to 635 nm, and detected by a photomultiplier tube, to test how the upconversion technology performs in a long range detection system. The upconversion approach is compared to an existing direct detection scheme using a near-IR detector with respect to signal-to-noise ratio and quantum efficiency. It is for the first time analyzed how the field-of-view of a receiver system, for long range detection, depends critically on the parameters for the nonlinear up-conversion process, and how to optimize these parameters in future systems.

Optica, vol. 3, no. 2, p. 127, (2016)

Active temporal and spatial multiplexing of photons

G. J. Mendoza et al.

The maturation of many photonic technologies from individual components to next-generation system-level circuits will require exceptional active control of complex states of light. A prime example is in quantum photonic technology: while single-photon processes are often probabilistic, it has been shown in theory that rapid and adaptive feedforward operations are sufficient to enable scalability. Here, we use simple “off-the-shelf” optical components to demonstrate active multiplexing—adaptive rerouting to single modes—of eight single-photon “bins” from a heralded source. Unlike other possible implementations, which can be costly in terms of resources or temporal delays, our new configuration exploits the benefits of both time and space degrees of freedom, enabling a significant increase in the single-photon emission probability. This approach is likely to be employed in future near-deterministic photon multiplexers with expected improvements in integrated quantum photonic technology.

Optics Express, vol. 23, no. 25, p. 32080-86, (2015)

Fully-integrated dual-wavelength all-fiber source for mode-locked square-shaped mid-IR pulse generation via DFG in PPLN

Karol Krzempek, Grzegorz Sobon, Jaroslaw Sotor, and Krzysztof M. Abramski

First demonstration of a dissipative soliton resonance (DSR), double-clad (DC) active fiber, mode-locked figure-8 laser (F8L) enabling simultaneous amplification of 1064 nm seed signal is presented. Appropriate design supported peak power clamping (PPC) effect in the laser resonator and enabled easy tuning of the generated, square-shaped pulses from 20 ns to 170 ns. By incorporating a circulator-based isolating element in the directional loop of the laser, record pulse energy of 2.13 µJ was achieved, directly at the output of the resonator. The usability of the unique dual-wavelength design was experimentally put to a test in a difference frequency generation (DFG) setup using periodically poled lithium niobate (PPLN) crystal.

Optics Express, vol. 23, no. 20, p. 26814-24, (2015)

Mid-infrared optical frequency combs based on difference frequency generation for molecular spectroscopy

Flavio C. Cruz, Daniel L. Maser, Todd Johnson, Gabriel Ycas, Andrew Klose, Fabrizio R. Giorgetta, Ian Coddington, and Scott A. Diddams

Mid-infrared femtosecond optical frequency combs were produced by difference frequency generation of the spectral components of a near-infrared comb in a 3-mm-long MgO:PPLN crystal. We observe strong pump depletion and 9.3 dB parametric gain in the 1.5 µm signal, which yields powers above 500 mW (3 µW/mode) in the idler with spectra covering 2.8 µm to 3.5 µm. Potential for broadband, high-resolution molecular spectroscopy is demonstrated by absorption spectra and interferograms obtained by heterodyning two combs.

Proc. SPIE 9370, Quantum Sensing and Nanophotonic Devices XII, 937025 (February 8, 2015)

High-power non linear frequency converted laser diodes fiber laser

O. Jensen, P. Andersen, and A. Hansen

We present different methods of generating light in the blue-green spectral range by nonlinear frequency conversion of tapered diode lasers achieving state-of-the-art power levels. In the blue spectral range, we show results using single-pass second harmonic generation (SHG) as well as cavity enhanced sum frequency generation (SFG) with watt-level output powers. SHG and SFG are also demonstrated in the green spectral range as a viable method to generate up to 4 W output power with high efficiency using different configurations.

Optics Letters, vol. 40, no. 14, pp. 3288–3291, (2015)

Fiber-laser-pumped, high-energy, mid-IR, picosecond optical parametric oscillator with a high-harmonic cavity

L. Xu, H.-Y. Chan, S. Alam, D. J. Richardson, and D. P. Shepherd

We demonstrate the generation of high-energy, mid-IR, picosecond pulses in a high-harmonic-cavity optical parametric oscillator (OPO) that has a relatively compact cavity with a length that is a small fraction of that required to match the pump repetition rate. The OPO, based on an MgO-doped periodically poled LiNbO3 crystal, is pumped by a fiber master-oscillator-power-amplifier system employing direct amplification and delivering 11-µJ, 150-ps pulses at 1035 nm. For a 1.554-m-long OPO cavity, resonating near-infrared signal pulses with a repetition rate that is the 193rd harmonic of the 1-MHz pump are demonstrated. The mid-infrared idler output pulses, tunable from 2300 nm to 3500 nm, are generated at a 1-MHz repetition rate and have energies as high as 1.5 µJ

Optics Express, vol. 23, no. 10, p. 12613-18, (2015)

High-energy, near- and mid-IR picosecond pulses generated by a fiber-MOPA-pumped optical parametric generator and amplifier

L. Xu, H.-Y. Chan, S. Alam, D. J. Richardson, and D. P. Shepherd

We report a high-energy picosecond optical parametric generator/amplifier (OPG/A) based on a MgO:PPLN crystal pumped by a fiber master-oscillator-power-amplifier (MOPA) employing direct amplification. An OPG tuning range of 1450-3615 nm is demonstrated with pulse energies as high as 2.6 µJ (signal) and 1.2 µJ (idler). When seeded with a ~100 MHz linewidth diode laser, damage-limited pulse energies of 3.1 µJ (signal) and 1.3 µJ (idler) have been achieved and the signal pulse time-bandwidth product is improved to ~2 times transform-limited. When seeded with a 0.3 nm-bandwidth filtered amplified spontaneous emission source, crystal damage is avoided and maximum pulse energies of 3.8 µJ (signal) and 1.7 µJ (idler) are obtained at an overall conversion efficiency of 45.

Physical Review A, vol. 91, no. 6, pp. 1–5, 2015, (2015)

Determination of transition frequencies in a single $^{138}Ba^{+}$ ion

E. A. Dijck, A. T. Grier, K. Jungmann, A. Mohanty, N. Valappol, and L. Willmann

Transition frequencies between low-lying energy levels in a single trapped ^{138}Ba+ ion have been measured with laser spectroscopy referenced to an optical frequency comb. By extracting the frequencies of one-photon and two-photon components of the line shape using an eight-level optical Bloch model, we achieved 0.1 MHz accuracy for the $5d^2D_{3/2}$–$6p^2P_{1/2}$ and $6s^2S_{1/2}$–$5d^2D_{3/2}$ transition frequencies, and 0.2 MHz for the $6s^2S_{1/2}$–$6p^2P_{1/2}$ transition frequency.

Applied Optics, vol. 54, no. 10, pp. 2594-2605, (2015)

Broadband and tunable optical parametric generator for remote detection of gas molecules in the short and mid-infrared

S. Lambert-Girard, M. Allard, M. Piché, and F. Babin

The development of a novel broadband and tunable optical parametric generator (OPG) is presented. The OPG properties are studied numerically and experimentally in order to optimize the generator's use in a broadband spectroscopic LIDAR operating in the short and mid-infrared. This paper discusses trade-offs to be made on the properties of the pump, crystal, and seeding signal in order to optimize the pulse spectral density and divergence while enabling energy scaling. A seed with a large spectral bandwidth is shown to enhance the pulse-to-pulse stability and optimize the pulse spectral density. A numerical model shows excellent agreement with output power measurements; the model predicts that a pump having a large number of longitudinal modes improves conversion efficiency and pulse stability.

Applied Optics, vol. 54, no. 7, pp. 1647-56, (2015)

Differential optical absorption spectroscopy lidar for mid-infrared gaseous measurements

S. Lambert-Girard, M. Allard, M. Piché, and F. Babin

This work presents the proof of concept of a remote sensing system designed for the detection of molecular species such as gas pollutants via active differential optical absorption spectroscopy in the short- and mid-wavelength infrared. The system includes an optical parametric generator generating broad linewidth pulses tunable between 1.5 and 3.8 µm. A telescope coupled to a grating spectrograph and an in-house gated HgCdTe avalanche photodiode measures the whole return spectrum from each pulse. Experiments show simultaneous detection in atmospheric air and inside a cell of H2O and CO2 at 2 µm, and H2O and CH4 at 3.3 µm. The detection limits for CO2 and CH4 are 158 and 1 ppm·m, respectively. A new algorithm is also presented enabling the determination of concentrations when spectra include strong absorption features.

Optics Letters, vol. 40, no. 4, pp. 593-6, (2015)

Compact, low-noise, all-solid-state laser system for stimulated Raman scattering microscopy

T. Steinle, V. Kumar, A. Steinmann, M. Marangoni, G. Cerullo, and H. Giessen

We present a highly stable and compact laser source for stimulated Raman scattering (SRS) microscopy. cw-seeding of an optical parametric amplifier pumped by a bulk femtosecond Yb-oscillator and self-phase modulation in a tapered fiber allow for broad tunability without any optical or electronic synchronization. The source features noise levels of the Stokes beam close to the shot-noise limit at MHz modulation frequencies. We demonstrate the superior performance of our system by SRS imaging of micrometer-sized polymer beads.

Applied Physics B, DOI 10.1007/s00340-015-6035-y, (2015)

Femtosecond optical parametric oscillators toward real-time dual-comb spectroscopy

Y. Jin, S. M. Cristescu, F. J. M. Harren, J. Mandon

We demonstrate mid-infrared dual-comb spectroscopy with an optical parametric oscillator (OPO) toward real-time field measurement. A singly resonant OPO based on a MgO-doped periodically poled lithium niobate (PPLN) crystal is demonstrated. Chirped mirrors are used to compensate the dispersion caused by the optical cavity and the crystal. A low threshold of 17 mW has been achieved. The OPO source generates a tunable idler frequency comb between 2.7 and 4.7 µm. Dual-comb spectroscopy is achieved by coupling two identical Yb-fiber mode-locked lasers to this OPO with slightly different repetition frequencies. A measured absorption spectrum of methane is presented with a spectral bandwidth of 300cm−1, giving an instrumental resolution of 0.4cm−1. In addition, a second OPO containing two MgO-doped PPLN crystals in a singly resonant ring cavity is demonstrated. As such, this OPO generates two idler combs (average power up to 220 mW), covering a wavelength range between 2.7 and 4.2 µm, from which a mid-infrared dual-comb Fourier transform spectrometer is constructed. By detecting the heterodyned signal between the two idler combs, broadband spectra of molecular gases can be observed over a spectral bandwidth of more than 350cm−1. This special cavity design allows the spectral resolution to be improved to 0.2cm−1 without locking the OPO cavity, indicating that this OPO represents an ideal high-power broadband mid-infrared source for real-time gas sensing.

Optics Communications, vol. 339, pp. 137–140, (2015)

Efficient generation of 509nm light by sum-frequency mixing between two tapered diode lasers

M. Tawfieq, O. B. Jensen, A. K. Hansen, B. Sumpf, K. Paschke, and P. E. Andersen

We demonstrate a concept for visible laser sources based on sum-frequency generation of beam combined tapered diode lasers. In this specific case, a 1.7 W sum-frequency generated green laser at 509 nm is obtained, by frequency adding of 6.17 W from a 978 nm tapered diode laser with 8.06 W from a 1063 nm tapered diode laser, inside a periodically poled MgO doped lithium niobate crystal. This corresponds to an optical to optical conversion efficiency of 12.1%. As an example of potential applications, the generated nearly diffraction-limited green light is used for pumping a Ti:sapphire laser, thus demonstrating good beam quality and power stability. The maximum output powers achieved when pumping the Ti:sapphire laser are 226 mW (CW) and 185 mW (mode-locked) at 1.7 W green pump power. The optical spectrum emitted by the mode-locked Ti:sapphire laser shows a spectral width of about 54 nm (FWHM), indicating less than 20 fs pulse width.

Applied Physics B, vol. 118, no. 3, pp. 343-351, (2015)

Mid-infrared multi-mode absorption spectroscopy, MUMAS, using difference frequency generation

H. Northern, S. O'Hagan, M. L. Hamilton, and P. Ewart

Multi-mode absorption spectroscopy of ammonia and methane at 3.3 µm has been demonstrated using a source of multi-mode mid-infrared radiation based on difference frequency generation. Multi-mode radiation at 1.56 µm from a diode-pumped Er:Yb:glass laser was mixed with a single-mode Nd:YAG laser at 1.06 µm in a periodically poled lithium niobate crystal to produce multi-mode radiation in the region of 3.3 µm. Detection, by direct multi-mode absorption, of NH3 and CH4 is reported for each species individually and also simultaneously in mixtures allowing measurements of partial pressures of each species.

Optics Letters, vol. 39, no. 16, pp. 4851-4, (2014)

Combining cw-seeding with highly nonlinear fibers in a broadly tunable femtosecond optical parametric amplifier at 42 MHz.

T. Steinle, S. Kedenburg, A. Steinmann, and H. Giessen

We report on a precisely tunable and highly stable femtosecond oscillator-pumped optical parametric amplifier at a 41.7 MHz repetition rate for spectroscopic applications. A novel concept based on cw-seeding of a first amplification stage with subsequent spectral broadening and shaping, followed by two further amplification stages, allows for precise sub-nanometer and gap-free tuning from 1.35 to 1.75 μm and 2.55 to 4.5 μm. Excellent spectral stability is demonstrated with deviations of less than 0.008% rms central wavelength and 1.6% rms bandwidth over 1 h. Spectral shaping of the seed pulse allows precise adjustment of both the bandwidth and the pulse duration over a broad range at a given central wavelength. Transform-limited pulses nearly as short as 107 fs are achieved. More than half a Watt of average power in the near- and more than 200 mW in the mid-infrared with power fluctuations less than 0.6% rms over 1 h provide an excellent basis for spectroscopic experiments. The pulse-to-pulse power fluctuations are as small as 1.8%. Further, we demonstrate for the first time, to the best of our knowledge, that by using hollow-core capillaries with highly nonlinear liquids as a host medium for self-phase modulation, the signal tuning range can be extended and covers the region from 1.4 μm up to the point of degeneracy at 2.07 μm. Hence, the idler covers 2.07 to 4.0 μm.

Applied Physics B, vol. 11, no. 4, pp. 987–993, (2014)

Yb-fiber amplifier pumped idler-resonant PPLN optical parametric oscillator producing 90 femtosecond pulses with high beam quality

L. Xu, J. S. Feehan, L. Shen, A. C. Peacock, D. P. Shepherd, D. J. Richardson, and J. H. V. Price

An idler-resonant femtosecond optical parametric oscillator (OPO) with near-diffraction-limited beam quality ($M^2 \sim 1.05$) at ~ 2.4 μm is demonstrated. The OPO is synchronously pumped by a femtosecond Yb-fiber amplifier system providing 130 fs pulses with an average power of 4.5 W at 1,050 nm and delivers 90 fs pulses with maximum average powers of 600 mW for the idler and 670 mW for the signal. Tunability is demonstrated across idler (signal) wavelengths from 2.2 to 2.6 μm (1.76–2.0 μm), limited only by the OPO mirrors. As a demonstration of the utility of the source, the idler pulses are used to generate a supercontinuum from 1,600 to 3,200 nm in a silicon-core fiber.

Applied Optics, vol. 53, no. 25, pp. 5726–32, (2014)

Sellmeier and thermo-optic dispersion formulas for the extraordinary ray of 5 mol. % MgO-doped congruent LiNbO3 in the visible, infrared, and terahertz regions

N. Umemura, D. Matsuda, T. Mizuno, and K. Kato

This paper reports the high-accuracy Sellmeier and thermo-optic dispersion formulas for the extraordinary ray of 5 mol. % MgO-doped congruent LiNbO3 that provide excellent reproduction of the temperature-dependent quasi-phase-matching conditions in the 0.39-4.95μm and 150-270 μm ranges. We believe that these equations would be highly useful for designing the frequency conversion system based on periodically poled MgO-doped LiNbO3.

Physical Review Letters, vol. 113, no. 6, p. 060502, (2014)

Distribution of Squeezed States through an Atmospheric Channel

C. Peuntinger, B. Heim, C. R. Müller, C. Gabriel, C. Marquardt, and G. Leuchs

Continuous variable quantum states of light are used in quantum information protocols and quantum metrology and known to degrade with loss and added noise. We were able to show the distribution of bright polarization squeezed quantum states of light through an urban freespace channel of 1.6 km length. To measure the squeezed states in this extreme environment, we utilize polarization encoding and a postselection protocol that is taking into account classical side information stemming from the distribution of transmission values. The successful distribution of continuous variable squeezed states is accentuated by a quantum state tomography, allowing for determining the purity of the state.

Optics Communications, vol. 327, pp. 3–6, (2014)

Simple, pulsed, polarization entangled photon pair source

N. Bruno, E. Zambrini Cruzeiro, A. Martin, and R. T. Thew

We report the realization of a fibred polarization entangled photon-pair source at 1560 nm based on a type-II nonlinear interaction and working in the picosecond regime. By taking advantage of a set of fibre filters, we deterministically separate the photons and project them into wavelength separable states. A standard entanglement measurement with a net interference visibility close to 1 proves the relevance of our approach as an enabling technology for entanglement-based quantum communication.

Optics Express, vol. 22, no. 15, pp. 18072–7, (2014)

High repetition rate femtosecond double pass optical parametric generator with more than 2 W tunable output in the NIR

H. Linnenbank and S. Linden

We demonstrate a highly efficient double pass optical parametric generator based on periodically poled MgO-doped congruent LiNbO3. More than two watts of tunable near-IR radiation (1370-1650 nm) are generated by directly pumping the system with 550 fs pulses from a 42 MHz repetition rate passively mode-locked Yb:KGW oscillator. Pulse durations below 200 fs were achieved without further compression techniques. The system is extremely efficient, compact, cost effective, easy to align and easy to operate, which makes it an interesting alternative to more complex optical parametric oscillators or optical parametric amplifiers.

Optics Letters, vol. 39, no. 11, pp. 3270–3, (2014)

Two-crystal mid-infrared optical parametric oscillator for absorption and dispersion dual-comb spectroscopy

Y. Jin, S. M. Cristescu, F. J. M. Harren, and J. Mandon

We present a femtosecond optical parametric oscillator (OPO) containing two magnesium-doped periodically poled lithium niobate crystals in a singly resonant ring cavity, pumped by two mode-locked Yb-fiber lasers. As such, the OPO generates two idler combs (up to 220 mW), covering a wavelength range from 2.7 to 4.2 µm, from which a mid-infrared dual-comb Fourier transform spectrometer is constructed. By detecting the heterodyning signal between the two idler beams a full broadband spectrum of a molecular gas can be observed over 250 cm^{-1} within 70 µs with a spectral resolution of 15 GHz. The absorption and dispersion spectra of acetylene and methane have been measured around 3000 cm^{-1}, indicating that this OPO represents an ideal broadband mid-infrared source for fast chemical sensing.

Optics Express, vol. 22, no. 8, pp. 9567-73, (2014)

Watt-level optical parametric amplifier at 42 MHz tunable from 1.35 to 4.5 µm coherently seeded with solitons

T. Steinle, A. Steinmann, R. Hegenbarth, and H. Giessen

We report on an optical parametric amplifier at high repetition rate of 41.7 MHz seeded by an optical soliton from a tapered fiber. Gap-free signal tuning from 1.35 µm to 1.95 µm with corresponding idler wavelengths from 2.2 µm to 4.5 µm is demonstrated. The system provides up to 1.8 W average power at 1.4 µm, more than 1.1 W up to 1.7 µm, and more than 400 mW up to 4.0 µm with a signal pulse duration of 200 to 300 fs. It is directly pumped by a solid-state oscillator providing up to 7.4 W at 1.04 µm wavelength with 425 fs pulse duration. Soliton-seeding is shown to lead to excellent pulse-to-pulse stability, but it introduces a timing-jitter on the millisecond timescale. Using a two-stage concept the timing-jitter is efficiently suppressed due to the passive synchronization of both conversion stages.

Optics Express, vol. 22, no. 4, pp. 4371–8, (2014)

Narrowband photon pair source for quantum networks

F. Monteiro, a Martin, B. Sanguinetti, H. Zbinden, and R. T. Thew

We demonstrate a compact photon pair source based on a periodically poled lithium niobate nonlinear crystal in a short cavity. This approach provides efficient, low-loss, mode selection that is compatible with standard telecommunication networks. Photons with a coherence time of 8.6 ns (116 MHz) are produced and their purity is demonstrated. A source brightness of 134 pairs (s. mW. MHz^{-1}) is reported. The cavity parameters are chosen such that the photon pair modes emitted can be matched to telecom ultra dense wavelength division multiplexing (U-DWDM) channel spacings. The high level of purity and compatibility with standard telecom networks is of great importance for complex quantum communication networks.

Nature Photonics, vol. 8, no. 2, pp. 153–159, (2014)

Stimulated Raman Scattering Microscopy with a Robust Fibre Laser Source

C. W. Freudiger, W. Yang, G. R. Holtom, N. Peyghambarian, X. S. Xie, and K. Q. Kieu

Stimulated Raman Scattering microscopy allows label-free chemical imaging and has enabled exciting applications in biology, material science, and medicine. It provides a major advantage in imaging speed over spontaneous Raman scattering and has improved image contrast and spectral fidelity compared to coherent anti-Stokes Raman. Wider adoption of the technique has, however, been hindered by the need for a costly and environmentally sensitive tunable ultra-fast dual-wavelength source. We present the development of an optimized all-fibre laser system based on the optical synchronization of two picosecond power amplifiers. To circumvent the high-frequency laser noise intrinsic to amplified fibre lasers, we have further developed a high-speed noise cancellation system based on voltage-subtraction autobalanced detection. We demonstrate uncompromised imaging performance of our fibre-laser based stimulated Raman scattering microscope with shot-noise limited sensitivity and an imaging speed up to 1 frame/s.

Fibers, vol. 1, no. 3, pp. 70–81, (2013)
Towards Water-Free Tellurite Glass Fiber for 2–5 µm Nonlinear Applications
X. Feng, J. Shi, M. Segura, N. White, P. Kannan, L. Calvez, X. Zhang, L. Brilland, and W. Loh
We report our recent progress on fabricating dehydrated tellurite glass fibers. Low OH content (1 ppm in weight) has been achieved in a new halogen-containing lead tellurite glass fiber. Low OH-induced attenuation of 10 dB/m has been confirmed in the range of 3–4 µm using three measurement methods. This shows the dehydrated halo-tellurite glass fiber is a promising candidate for nonlinear applications in a 2–5 µm region.

Optics express, vol. 21, no. 17, pp. 20023–31 (2013)
DFG-based mid-IR generation using a compact dual-wavelength all-fiber amplifier for laser spectroscopy applications
K. Krzempek, G. Sobon, and K. M. Abramski
We demonstrate a compact mid-infrared (mid-IR) radiation source based on difference frequency generation (DFG) in periodically poled lithium niobate (PPLN) crystal. The system incorporates a dual-wavelength master oscillator power amplifier (MOPA) source capable of simultaneous amplification of 1064 nm and 1548 nm signals in a common active fiber co-doped with erbium and ytterbium ions. Two low-power seed lasers were amplified by a factor of 14.4 dB and 23.7 dB for 1064 nm and 1548 nm, respectively and used in a nonlinear DFG setup to generate 1.14 mW of radiation centered at 3.4 µm. The system allowed for open-path detection of methane (CH4) in ambient air with estimated minimum detectable concentration at a level of 26 ppbv.

Optics express, vol. 21, no. 16, pp. 18949–54 (2013)
Halo-tellurite glass fiber with low OH content for 2-5µm mid-infrared nonlinear applications
X. Feng, J. Shi, M. Segura, N. M. White, P. Kannan, W. H. Loh, L. Calvez, X. Zhang, and L. Brilland
We report the fabrication of new dehydrated halo-tellurite glass fibers with low OH content (1ppm in weight) and low OH-induced attenuation of 10dB/m in 3-4 µm region. It shows halo-tellurite glass fibers a promising candidate for nonlinear applications in 2-5µm region.

Optics express, vol. 21, no. 15, pp. 18371–86 (2013)
Squeezed light in an optical parametric oscillator network with coherent feedback quantum control
O. Crisafulli, N. Tezak, D. B. S. Soh, M. A. Armen, and H. Mabuchi
We present squeezing and anti-squeezing spectra of the output from a degenerate optical parametric oscillator (OPO) network arranged in different coherent quantum feedback configurations. One OPO serves as a quantum plant, the other as a quantum controller. The addition of coherent feedback enables shaping of the output squeezing spectrum of the plant, and is found to be capable of pushing the frequency of maximum squeezing away from the optical driving frequency and broadening the spectrum over a wider frequency band. The experimental results are in excellent agreement with the developed theory, and illustrate the use of coherent quantum feedback to engineer the quantum-optical properties of the plant OPO output.

Applied Physics B, DOI 10.1007/s00340-013-5605-0 (2013)
All-solid-state continuous-wave laser systems for ionization, cooling and quantum state manipulation of beryllium ions
H.-Y. Lo, J. Alonso, D. Kienzler, B. C. Keitch, L. E. de Clercq, V. Negnevitsky and J. P. Home
We describe laser systems for photoionization, Doppler cooling, and quantum state manipulation of beryllium ions. For photoionization of neutral beryllium, we have developed a continuous-wave 235 nm source obtained by two stages of frequency doubling from a diode laser at 940 nm. The system delivers up to 400 mW at 470 nm and 28 mW at 235 nm. For control of the beryllium ion, three laser wavelengths at 313 nm are produced by sum-frequency generation and second-harmonic generation from four infrared fiber lasers. Up to 7.2 W at 626 nm and 1.9 W at 313 nm are obtained using two pump beams at 1051 and 1551 nm. Intensity drifts of around 0.5 % per hour have been measured over 8 h at a 313 nm power of 1 W. These systems have been used to load beryllium ions into a segmented ion trap.

Proceedings of SPIE Vol. 8726, 87260X (2013)
Continuous-wave near-photon counting spectral imaging detector in the mid-infrared by upconversion
J. S. Dam, P. Tidemand-Lichtenberg, and C. Pedersen
Low noise upconversion of IR images by three-wave mixing, can be performed with high efficiency when mixing the object radiation with a powerful laser field inside a highly non-linear crystal such as periodically poled Lithium Niobate. Since IR cameras are expensive and have high levels of intrinsic noise, we suggest to convert the wavelength from the mid infrared to the visible/NIR wavelength for simple detection using CCD cameras. The intrinsic noise in cameras has two main contributions. First, read noise originating from the charge to signal read-out electronics. This noise source is usually measured in number of electrons. The second noise source is usually

referred to as dark noise, which is the background signal generated over time. Dark noise is usually measured in electrons per pixel per second. For silicon cameras certain models like EM-CCD have close to zero read noise, whereas high-end IR cameras have read noise of hundreds of electrons. The dark noise for infrared cameras based on semiconductor materials is also substantially higher than for silicon cameras, typical values being millions of electrons per pixel per second for cryogenically cooled cameras whereas peltier cooled CCD cameras have dark noise measured in fractions of electrons per pixel per second. An ideal solution thus suggest the combination of an efficient low noise image wavelength conversion system combined with low noise silicon based cameras for low noise imaging in the IR region. We discuss image upconversion as a means to do low noise conversion of IR light to visible light. We demonstrate system noise performance orders of magnitude lower than existing cryogenic cooled IR cameras.

Applied Physics B, DOI 10.1007/s00340-013-5434-1 (2013)
A picosecond near-infrared laser source based on a self-seeded optical parametric generator
P. K. Upputuri, H. Wang
We report on the design and development of a new type of near-IR laser source. The source comprises of an optical parametric generator (OPG) and a second harmonic generator (SHG) pumped by an 80-MHz, 1064-nm, 7-ps Nd:YVO_4 laser. The OPG is self-seeded with a fraction of its own signal output, which significantly enhances its conversion efficiency. The SHG doubles the frequency of OPG signal to produce a coherent output. The final output beam has a tunable wavelength near 800 nm, an average power of over 1 W, and a pulse duration around 5 ps. The M^2-factor of the output beam can reach 1.1 after spatial filtering. With the new laser source, we have successfully demonstrated coherent anti-Stokes Raman scattering microscopy on 1 µm polystyrene beads, which shows that it has the potential to be a substitute for a picosecond optical parametric oscillator in certain microscopy or spectroscopy applications.

Optics Express, Vol. 21, Issue 8, pp. 9780-9791 (2013)
Frequency-comb-referenced multi-wavelength profilometry for largely stepped surfaces
S. Hyun, M. Choi, B. J. Chun, S. Kim, S. W. Kim, and Y. J. Kim
3-D profiles of discontinuous surfaces patterned with high step structures are measured using four wavelengths generated by phase-locking to the frequency comb of an Er-doped fiber femtosecond laser stabilized to the Rb atomic clock. This frequency-comb-referenced method of multi-wavelength interferometry permits extending the phase non-ambiguity range by a factor of 64,500 while maintaining the sub-wavelength measurement precision of single-wavelength interferometry. Experimental results show a repeatability of 3.13 nm (one-sigma) in measuring step heights of 1800, 500, and 70 µm. The proposed method is accurate enough for the standard calibration of gauge blocks and also fast to be suited for the industrial inspection of microelectronics products.

Optics Letters, Vol. 37, Issue 18, pp. 3861-3863 (2012)
Generation of 43 W of quasi-continuous 780 nm laser light via high-efficiency, single-pass frequency doubling in periodically poled lithium niobate crystals
S. Chiow, T. Kovachy, J. M. Hogan, and M. A. Kasevich
We demonstrate high-efficiency frequency doubling of the combined output of two 1560 nm 30 W fiber amplifiers via single pass through periodically poled lithium niobate (PPLN) crystals. The temporal profile of the 780 nm output is controlled by adjusting the relative phase between the seeds of the amplifiers. We obtain a peak power of 34W of 780 nm light by passing the combined output through one PPLN crystal, and a peak power of 43 W by passing through two cascading PPLN crystals. This source provides high optical power, excellent beam quality and spectral purity, and agile frequency and amplitude control in a simple and compact setup, which is ideal for applications such as atom optics using Rb atoms.

Review of Scientific Instruments 83, 083115 (2012)
Cryogenic linear Paul trap for cold highly charged ion experiments
M. Schwarz, O. O. Versolato, A. Windberger, F. R. Brunner, T. Ballance, S. N. Eberle, J. Ullrich, P. O. Schmidt, A. K. Hansen, A. D. Gingell, M. Drewsen, and J. R. Crespo López-Urrutia
Storage and cooling of highly charged ions require ultra-high vacuum levels obtainable by means of cryogenic methods. We have developed a linear Paul trap operating at 4 K capable of very long ion storage times of about 30 h. A conservative upper bound of the H_2 partial pressure of about 10^{-15} mbar (at 4 K) is obtained from this. External ion injection is possible and optimized optical access for lasers is provided, while exposure to black body radiation is minimized. First results of its operation with atomic and molecular ions are presented. An all-solid state laser system at 313 nm has been set up to provide cold Be^+ ions for sympathetic cooling of highly charged ions.

Optics Letters, Vol. 37, Issue 21, pp. 4561-4563 (2012)
Degenerate 1 GHz repetition rate femtosecond optical parametric oscillator
M. Vainio, M. Merimaa, L. Halonen, and K. Vodopyanov

We report a degenerate femtosecond optical parametric oscillator (OPO) that is synchronously pumped by a mode-locked Ti:sapphire laser at 1 GHz repetition rate. The OPO produces an 85 nm (10 THz) wide frequency comb centered at 1.6 µm. Stable long-term operation with >100mW of average output power has been achieved.

Applied Physics B, Vol. 109, Issue 3, pp 423-432 (2012)

Combining a DS-DBR laser with QPM-DFG for mid-infrared spectroscopy

K. E. Whittaker, L. Ciaffoni, G. Hancock, M. Islam, R. Peverall and G. A. D. Ritchie

Studies into the suitability of a novel, widely tunable telecom L-band (1563–1613 nm) digital supermode distributed Bragg reflector (DS-DBR) laser for spectroscopy in the mid-IR are presented. Light from the DS-DBR laser was mixed with 1064 nm radiation in a periodically poled lithium niobate (PPLN) crystal to generate mid-IR light by quasi phase matching difference frequency generation (QPM-DFG). The resultant continuous wave radiation covered the range 3000–3200 cm^{-1} with powers of up to 2.6 µW. The use of such laser light for spectroscopic applications was illustrated by performing absorption experiments on both narrow-band and broad-band absorbers, namely methane (CH_4) and methanethiol (CH_3SH). Wavelength modulation spectroscopy (WMS) on CH4 demonstrated that the modulation characteristics of the DS-DBR laser observed in the near-IR were transposed to the mid-IR and yielded a sensitivity of 3.1×10−6 $cm^{-1}Hz^{-1/2}$ over a 47 cm path length. In the CH3SH spectrum, the absorption feature at 3040 cm−1 was identified as a potential useful region for monitoring this biomarker in exhaled breath at reduced pressures.

Applied Physics B, Vol. 109, Issue 2, pp. 333-343 (2012)

A DFG-based cavity ring-down spectrometer for trace gas sensing in the mid-infrared

K. E. Whittaker, L. Ciaffoni, G. Hancock, R. Peverall and G. A. D. Ritchie

Continuing studies into an all-diode laser-based 3.3µm difference frequency generation cavity ring-down spectroscopy system are presented. Light from a 1,560 nm diode laser, amplified by an erbium-doped fibre amplifier, was mixed with 1,064 nm diode laser radiation in a bulk periodically poled lithium niobate crystal to generate 16µW of mid-IR light at 3,346 nm with a conversion efficiency of 0.05%$W^{-1}cm^{-1}$. This radiation was coupled into a 77 cm long linear cavity with average mirror reflectivities of 0.9996, and a measured baseline ring-down time of 6.07±0.03µs. The potential of such a spectrometer was illustrated by investigating the P(3) transition in the fundamental ν_3F_2 band of CH4 both in a 7.5 ppmv calibrated mixture of CH_4 in air and in breath samples from methane and non-methane producers under conditions where the minimum detectable absorption coefficient (α_{min}) was 2.8 x $10^{-8}cm^{-1}$ over 6 s using a ring-down time acquisition rate of 20 Hz. Allan variance measurements indicated an optimum α_{min} of 2.9 x $10^{-9}cm^{-1}$ over 44 s.

Nature Photonics, DOI: 10.1038/NPHOTON.2012.231 (2012)

Room-temperature mid-infrared single-photon spectral imaging

J. S. Dam, P. Tidemand-Lichtenberg and C. Pedersen

The spectral imaging and detection of mid-infrared wavelengths is emerging as an enabling technology of great technical and scientific interest, primarily because important chemical compounds display unique and strong mid-infrared spectral fingerprints that reveal valuable chemical information. Modern quantum cascade lasers have evolved as ideal coherent mid-infrared excitation sources, but simple, low-noise, room-temperature detectors and imaging systems lag behind. We address this need by presenting a novel, field-deployable, upconversion system for sensitive, two-dimensional, mid-infrared spectral imaging. A room-temperature dark noise of 0.2 photons/spatial element/second is measured, which is a billion times below the dark noise level of cryogenically cooled InSb cameras. Single-photon imaging and a resolution of up to 200 × 100 spatial elements are obtained with a record-high continuous-wave quantum efficiency of ~20% for polarized incoherent light at 3 µm. The proposed method is relevant for existing and new mid-infrared applications such as gas analysis and medical diagnostics.

Optics Express, Vol. 20, Issue 13, pp. 13958-13965 (2012)

Sensitivity enhancement of fiber-laser-based stimulated Raman scattering microscopy by collinear balanced detection technique

K. Nose, Y. Ozeki, T. Kishi, K. Sumimura, N. Nishizawa, K. Fukui, Y. Kanematsu, and K. Itoh

We propose the collinear balanced detection (CBD) technique for noise suppression in fiber laser (FL)-based stimulated Raman scattering (SRS) microscopy. This technique reduces the effect of laser intensity noise at a specific frequency by means of pulse splitting and recombination with a time delay difference. We experimentally confirm that CBD can suppress the intensity noise of second harmonic (SH) of Er-FL pulses by 13dB.The measured noise level including the thermal noise is higher by only ~1.4 dB than the shot noise limit. To demonstrate SRS imaging, we use 4-ps SH pulses and 3-ps Yb-FL pulses, which are synchronized subharmonically with a jitter of 227 fs. The effectiveness of the CBD technique is confirmed through SRS imaging of a cultured HeLa cell.

Optics Express, Vol. 20, Issue 8, pp. 8915-8919 (2012)

11W narrow linewidth laser source at 780nm for laser cooling and manipulation of Rubidium

S. S. Sané, S. Bennetts, J. E. Debs, C. C. N. Kuhn, G. D. McDonald, P. A. Altin, J. D. Close, and N. P. Robins

We present a narrow linewidth continuous laser source with over 11 W output power at 780 nm, based on single-pass frequency doubling of an amplified 1560 nm fibre laser with 36% efficiency. This source offers a combination of high power, simplicity, mode quality and stability. Without any active stabilization, the linewidth is measured to be below 10 kHz. The fibre seed is tunable over 60 GHz, which allows access to the D2 transitions in 87Rb and 85Rb, providing a viable high-power source for laser cooling as well as for large-momentum-transfer beamsplitters in atom interferometry. Sources of this type will pave the way for a new generation of high flux, high duty-cycle degenerate quantum gas experiments.

Proc. SPIE 8237, Fiber Lasers IX: Technology, Systems, and Applications, 82373W (2012)
Electronic synchronization of gain-switched laser diode seeded fiber amplifiers
L. Abrardi, T. Feurer
We present a hybrid laser system based on all-fiber amplification of a gain-switched laser diode. The diode emits low energy pulses with several tens of picoseconds pulse duration at a wavelength of 1550 nm and a repetition rate of 1 MHz. The three-stage fiber amplifier reaches an overall gain of 55 dB boosting the pulse energy to 0.48 µJ. Much care is taken to preserve an almost bandwidth limited pulse with a spectral width of 0.1 nm and negligible spectral broadening due to nonlinearities. The laser system has been designed such that two or more can be electronically synchronized with the aim to combine them for exploring frequency mixing scenarios. Here, we report first cross-correlation measurements of two synchronized laser systems and present a method to characterize the relative timing-jitter.

Atmospheric and Oceanic Optics, Vol. 25, No. 1, pp. 77–81 (2012)
Optical Parametric Oscillator within 2.4–4.3 µm Pumped with a Nanosecond Nd:YAG Laser
D. B. Kolker, R. V. Pustovalova, M. K. Starikova, A. I. Karapuzikov, A. A. Karapuzikov, O. M. Kuznetsov, and Yu. V. Kistenev
An optical parametric oscillator has been designed on the basis of MgO:PPLN periodic structure. A compact nanosecond Nd:YAG laser has been used as a pump source at 1.053 µm. The pump pulse length is 5–7 ns at a maximum pulse energy of 300 µJ and a frequency of 1000–5000 Hz. The oscillation threshold is 22 µJ at 3 µm and 48 µJ at 4.3 µm. The maximum conversion efficiency from incident pump power to the idler output is 3.9%.

JOSA B, Vol. 29, Issue 1, pp. 144-152 (2012)
Green-pumped, picosecond MgO:PPLN optical parametric oscillator
F. Kienle, D. Lin, S. Alam, H. S. S. Hung, C. B. E. Gawith, H. E. Major, D. J. Richardson, and D. P. Shepherd
We investigate the performance of a magnesium-oxide-doped periodically poled lithium niobate crystal (MgO:PPLN) in an optical parametric oscillator (OPO) synchronously pumped by 530nm, 20ps, 230MHz pulses with an average power of up to 2W from a frequency-doubled, gain-switched LD seed and a multistage Yb:fiber amplifier system. The OPO produces ~165mW (signal, 845nm) and ~107mW (idler, 1421nm) of average power for ~1W of pump power and can be tuned from ~800 to 900nm (signal) and 1.28 to 1.54µm (idler). Observations of photorefraction and green-induced infrared absorption in different operational regimes of the MgO:PPLN OPO are described and the role of peak intensity and average power are investigated, both with the aim to find the optimal operating regime for pulsed systems.

Applied Physics B, Vol. 105, Issue 4, pp. 741-748 (2011)
A 750-mW, continuous-wave, solid-state laser source at 313nm for cooling and manipulating trapped $^{9}Be^{+}$ ions
A. C. Wilson, C. Ospelkaus, A. P. VanDevender, J. A. Mlynek, K. R. Brown, D. Leibfried and D. J. Wineland
We present a solid-state laser system that generates 750 mW of continuous-wave, single-frequency output at 313 nm. Sum-frequency generation with fiber lasers at 1550 and 1051 nm produces up to 2 W at 626 nm. This visible light is then converted to ultraviolet by cavity-enhanced second-harmonic generation. The laser output can be tuned over a 495-GHz range, which includes the 9Be+ laser cooling and repumping transitions. This is the first report of a narrow-linewidth laser system with sufficient power to perform fault-tolerant quantum-gate operations with trapped $^{9}Be^{+}$ ions by use of stimulated Raman transitions.

Optics Letters, Vol. 36, Issue 19, pp. 3909-3911 (2011)
Generation of 520 mW pulsed blue light by frequency doubling of an all-fiberized 978 nm Yb-doped fiber laser source
M. Laroche, C. Bartolacci, B. Cadier, H. Gilles, S. Girard, L. Lablonde, and T. Robin
Pulsed blue light at 489nm has been generated by second-harmonic-generation of a nanosecond pulsed master oscillator power amplifier system based on a short Yb^{3+} doped single-mode fiber amplifier at 978nm and an external-cavity diode laser as seed source. The Yb^{3+}-doped fiber was core-pumped by a W type Nd^{3+} doped doubleclad fiber laser operating on the transition near 930nm ($^{4}F_{3/2} \rightarrow {}^{4}I_{9/2}$). 520mW of average power was generated at 489nm using a periodically poled MgO:LiNbO3, corresponding to a conversion efficiency of 34%.

Applied Physics B, Vol. 104, Issue 4, pp. 779-804 (2011)

Noise performance of a feed-forward scheme for carrier-envelope phase stabilization

S. Koke, A. Anderson, H. Frei, A. Assion and G. Steinmeyer

The noise performance of a feed-forward scheme for carrier-envelope phase stabilization is discussed. This scheme uses an acousto-optic frequency shifter to directly correct for fluctuations of the carrier-envelope phase in a pulse train emitted by a mode-locked laser without manipulating the intracavity dispersion. Generation of zero-offset frequency combs is demonstrated. Furthermore, it is shown that pump laser noise has only a minor effect on the achievable performance. Limited only by the travel time of the acoustic wave in the shifter, pump laser noise can be corrected up to near-megahertz frequencies, which yields superior noise performance compared to traditional feedback operation. Residual phase jitters down to 45mrad are experimentally verified.

Optics Letters, Vol. 36, Issue 3, pp. 361-363 (2011)

465nm laser sources by intracavity frequency doubling using a 49-edge-emitters laser bar

K. Li, H. Wang, N. J. Copner, C. B. E. Gawith, I. G. Knight, H.-U. Pfeiffer, B. Musk, and G. Moss

A compact blue laser was generated by intracavity frequency doubling based on quasi-phase-matched second harmonic generation (SHG) in a MgO-doped periodically poled lithium niobate bulk crystal. A 49 single-transversemode edge-emitters laser bar with antireflective coating was used as a pump source. An optical output power of 1:2W SHG of blue lights at 465nm is generated at 45A injection current, equivalent to an overall wall-plug efficiency of 1.33%.

Optics letters, vol. 35, no. 19, pp. 3282–4 (2010)

Ultrabroadband background-free coherent anti-Stokes Raman scattering microscopy based on a compact Er:fiber laser system

R. Selm, M. Winterhalder, A. Zumbusch, G. Krauss, T. Hanke, A. Sell, and A. Leitenstorfer

We demonstrate a scheme for efficient coherent anti-Stokes Raman scattering (CARS) microscopy free of nonresonant background. Our method is based on a compact Er:fiber laser source. Impulsive excitation of molecular resonances is achieved by an 11 fs pulse at 1210 nm. Broadband excitation gives access to molecular resonances from 0 cm^{-1} up to 4000 cm^{-1}. Time-delayed narrowband probing at 775 nm enables sensitive and high-speed spectral detection of the CARS signal free of nonresonant background with a resolution of 10cm^{-1}.

Optics Letters, Vol. 35, Issue 21, pp. 3580-3582 (2010)

Compact, high-pulse-energy, picosecond, optical parametric oscillator

F. Kienle, P. S. Teh, S. Alam, C. B. E. Gawith, D. C. Hanna, D. J. Richardson, and D. P. Shepherd

We report a high-energy optical parametric oscillator (OPO) synchronously-pumped by a 7.19MHz, Yb-fiber-amplified, picosecond, gain-switched laser diode. The 42m long ring cavity maintains a compact design through the use of an intra-cavity optical fiber. The periodically-poled MgO-doped $LiNbO_3$ OPO provides output pulse energies as high as 0.49µJ at 1.5µm (signal) and 0.19µJ at 3.6µm (idler). Tunability from 1.5µm to 1.7µm and from 2.9µm to 3.6µm is demonstrated and typical M^2-values of 1.3 by 1.5 and 1.9 by 2.8 are measured for the signal and idler, respectively, at high power.

Conference on Lasers and Electro-Optics (CLEO/QELS 2010), Baltimore, Maryland, CThZ7

A picosecond Optical Parametric Oscillator synchronously pumped by an amplified gain-switched laser diode

F. Kienle, K. K. Cheng, S. Alam, C. B. E. Gawith, J. I.Mackenzie, D. C. Hanna, D. J. Richardson, and D. P. Shepherd

We demonstrate a picosecond optical parametric oscillator synchronously pumped by a fiber-amplified gain-switched laser diode. Up to 7.3W at 1.54µm and 3.1W at 3.4µm is obtained at pulse repetition rates between 114.8 and 918.4MHz.

Optics Express, Vol. 18, Issue 8, pp. 7602-7610 (2010)

High-power, variable repetition rate, picosecond optical parametric oscillator pumped by an amplified gain-switched diode

F. Kienle, K. K. Cheng, S. Alam, C. B. E. Gawith, J. I.Mackenzie, D. C. Hanna, D. J. Richardson, and D. P. Shepherd

We demonstrate a picosecond optical parametric oscillator (OPO) that is synchronously pumped by a fiber-amplified gain-switched laser diode. At 24W of pump power, up to 7.3W at 1.54µm and 3.1W at 3.4µm is obtained in separate output beams. The periodically poled MgO-doped LiNbO3 OPO operates with ~17ps pulses at a fundamental repetition rate of 114.8MHz but can be switched to higher repetition rates up to ~1GHz. Tunabilty between 1.4µm and 1.7µm (signal) and 2.9µm and 4.4µm (idler) is demonstrated by translating the nonlinear crystal to access different poling-period gratings and typical M2 values of 1.1 by 1.2 (signal) and 1.6 by 3.2 (idler) are measured at high power for the singly resonant oscillator.

- Nature Photonics, Vol. 4, pp. 462-465 (2010)
  Direct frequency comb synthesis with arbitrary offset and shot-noise-limited phase noise
  S. Koke, C. Grebing, H. Frei, A. Anderson, A. Assion and G. Steinmeyer
  Carrier-envelope phase stabilization has opened an avenue towards achieving frequency metrology with unprecedented precision and optical pulse generation on the previously inaccessible attosecond timescale. Recently, sub-100-as pulsegeneration has been demonstrated, approaching the timescale of the fastest transients in atomic physics. However, further progress in attophysics appears to be limited by the performance of the traditional feedback approach used for carrier-envelope phase stabilization. Here, we demonstrate a conceptually different self-referenced feed-forward approach to phase stabilization. This approach requires no complicated locking electronics, does not compromise laser performance, and is demonstrated with 12-as residual timing jitter, which is below the atomic unit of time. This surpasses the precision of previous methods by more than a factor of five and has potential for resolving even the fastest transients in atomic or molecular physics. Such shot-noise-limited comb synthesis may also simplify progress in current research in frequency metrology.

- Laser Physics, Vol. 20, No. 7, pp. 1568-1571 (2010)
  52% optical-to-optical conversion efficiency in a compact 1.5 W 532 nm second harmonic generation laser with intracavity periodically-poled MgO:LiNbO3
  M. Zhou, B. X. Yan, G. Bao, Y. Zhang, C. B. E. Gawith, D. D. Wang, Y. Qi and Y. Bi
  Intracavity second-harmonic generation of 1.56 and 1.52 W continuous-wave 532 nm green laser radiation was obtained by quasi-phase matching in periodically-poled MgO:LiNbO3 (MgO:PPLN) crystals with lengths of 2 and 1 mm, respectively. The maximum optical-to-optical efficiency achieved was 52%. The intracavity temperature bandwidth was 15 and 12°C for 1 mm crystal and 2 mm crystal, respectively.

- Photonics West 2010, OPS Lasers II: 7578-37 (26th January 2010)
  532nm laser sources based on intracavity frequency doubling of multi-edge-emitting diode lasers
  K. Li, N. Copner, C. B. E. Gawith and I. G. Knight
  532nm green light source of 1.2W output is generated by intra-cavity frequency doubling (ICFD) of a multi-edge-emitter laser bar using a MgO-doped periodically poled lithium niobate (MgO:PPLN) bulk crystal. The measured M2 values of green beam are 11.9 and 2.6 along the x- and y-axes respectively. To our knowledge this is the first demonstration of the ICFD of a multi-edge-emitter laser bar.

- Optics Letters, Vol. 34, Issue 22, pp. 3472-3474 (2009)
  Compact 1.3 W green laser by intracavity frequency doubling of a multi-edge-emitter laser bar using a MgO:PPLN crystal
  K. Li, A. Yao, N. J. Copner, C. B. E. Gawith, I. G. Knight, H. Pfeiffer, and B. Musk
  A compact green laser of 1.3 W output at 534.7 nm is generated by intracavity frequency doubling (ICFD) of a 49 edge-emitter laser bar using a MgO-doped (PPLN) bulk crystal. The measured M^2 values of green beam are 12.1 and 2.9 along the slow and fast axes, respectively. To our knowledge, this is the first demonstration of the ICFD of multi-edge-emitters laser bar.

- European Conference on Lasers and Electro-Optics (CLEO/Europe-EQEC 2009), Munich, CA.P.5 TUE
  Intra-cavity frequency doubling of an electrically pumped edge-emitting 980 nm laser diode with PPLN
  K. Li, A. Yao, N. J. Copner, C. B. E. Gawith, I. G. Knight
  A novel intra-cavity frequency doubling of an electrically pumped edge-emitting laser diode was demonstrated for the first time to our knowledge. The experimental data agree well with the numerical results based on our model.

- Optics Express, Vol. 17, Issue 24, pp. 22073-22080 (2009)
  Blue light generated by intra-cavity frequency doubling of an edge-emitting diode laser with a periodically poled LiNbO3 crystal
  K. Li, A. Yao, N. J. Copner, C. B. E. Gawith, I. G. Knight, H. Pfeiffer, and B. Musk
  We demonstrate for the first time to our knowledge intra-cavity frequency doubling (ICFD) of an edge-emitter diode laser using a 10 mm-long 5.0 µm periodically poled LiNbO3 (PPLN) crystal. An optical output power of 33 mW second harmonic blue light at 490.5 nm is generated at 1.0 A injection current, equivalent to an overall wall-plug efficiency of 1.8%. The measured M2 values of blue beam are 1.7 and 2.4 along the fast and slow axis.

- Applied Optics, Vol. 48, Issue 13, pp. 2600-2606 (2009)
  Pump-enhanced difference-frequency generation at 3.3 µm
  M. F. Witinski, J. B. Paul, and J. G. Anderson

The demonstration of continuous wave intracavity difference-frequency generation in the mid-infrared (mid-IR) is presented. A cavity for pump laser enhancement is constructed around a periodically poled lithium niobate crystal, and the cavity length is locked to the frequency of the pump laser using the Pound-Drever-Hall technique, producing a gain of 12 in the resultant idler power compared to the single-pass case. A widely tunable single-mode 3.3 µm idler beam with a power of nearly 10 mW is available for direct absorption spectroscopy. The pump-enhancement method demonstrated here should be readily scalable to produce hundreds of milliwatts of mid-IR light by using higher power signal and pump lasers.

Optics Letters Vol. 34, Issue 7, pp. 1093-1095 (2009)

Continuous-wave sodium D2 resonance radiation generated in single-pass sum-frequency generation with periodically poled lithium niobate

J. Yue, C. She, B. Williams, J. Vance, P. Acott, and T. Kawahara

With two cw single-mode Nd:YAG lasers at 1064 and 1319 nm and a periodically poled lithium niobate crystal, 11 mW of 2 kHz/100 ms bandwidth single-mode tunable 589 nm cw radiation has been detected using single-pass sum-frequency generation. The demonstrated conversion efficiency is ~3.2%[$W^{-1}cm^{-1}$]. This compact solid-state light source has been used in a solid-state-dye laser hybrid sodium fluorescence lidar transmitter to measure temperatures and winds in the upper atmosphere (80-105 km); it is being implemented into the transmitter of a mobile all-solid-state sodium temperature and wind lidar under construction.

Optics and Lasers in Engineering, Vol. 47, Issue 5, pp. 589-593 (2009)

Study of quasi-phase matching wavelength acceptance bandwidth for periodically poled LiNbO3 crystal-based difference-frequency generation

Z. Cao, X. Gao, W. Chen, H. Wang, W. Zhang and Z. Gong

The temperature tuning characteristics of quasi-phase matching (QPM) wavelength acceptance bandwidth in a uniform periodically poled lithium niobate (PPLN) based on difference-frequency generation (DFG) are studied theoretically and experimentally. This paper proposes a PPLN device consisting of several segments of different temperatures to obtain a more desirable performance for the QPM-DFG. The result shows that through the tuning of temperature, the bandwidth can be changed considerably and the method was proved suitable and accurate to calculate QPM wavelength acceptance bandwidth of DFG in a uniform PPLN crystal for temperatures between room temperature and 180 °C and mid-infrared (mid-IR) wavelengths ranging from 2.8 to 4.8 µm.

Optics Express, Vol. 16, Issue 21, pp. 17060-17069 (2008)

Fast and simple characterization of a photon pair source

F. Bussières, J. A. Slater, N. Godbout, and W. Tittel

We present an exact model of the detection statistics of a probabilistic source of photon pairs from which a fast, simple and precise method to measure the source's brightness and photon channel transmissions is demonstrated. We measure such properties for a source based on spontaneous parametric downconversion in a periodically poled LiNbO3 crystal producing pairs at 810 and 1550 nm wavelengths. We further validate the model by comparing the predicted and measured values for the $g^{(2)}(0)$ of a heralded single photon source over a wide range of the brightness. Our model is of particular use for monitoring and tuning the brightness on demand as required for various quantum communication applications. We comment on its applicability to sources involving spectral and/or spatial filtering.

Applied Physics B: Lasers and Optics, Vol. 92, No. 2, pp. 271-279 (2008)

Mid-infrared laser absorption spectrometers based upon all-diode laser difference frequency generation and a room temperature quantum cascade laser for the detection of CO, N_2O and NO

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We describe the performance of two mid-infrared laser spectrometers for carbon monoxide, nitrous oxide and nitric oxide detection. The first spectrometer for CO and N_2O detection around 2203 cm^{-1} is based upon all-diode laser difference frequency generation (DFG) in a quasi-phase matched periodically-poled lithium niobate (PPLN) crystal using two continuous-wave room-temperature distributed feedback diode lasers at 859 and 1059 nm. We also report on the performance of a mid-infrared spectrometer for NO detection at ~1900 cm^{-1} based upon a thermoelectrically-cooled continuous-wave distributed feedback quantum cascade laser (QCL). Both spectrometers had a single-pass optical cell and a thermoelectrically cooled HgCdZnTe photovoltaic detector. Typical minimum detection limits of 2.8 ppmv for CO, 0.6 ppmv for N_2O and 2.7 ppmv for NO have been demonstrated for a 100 averaged spectra acquired within 1.25 s and a cell base length of 21 cm at ~100 Torr. Noise-equivalent absorptions of 10^{-5} and 10^{-4} $Hz^{-1/2}$ are typically demonstrated for the QCL and the DFG based spectrometers, respectively.

NASA Earth Science Technology Conference (2008), B8P2

Development of Miniaturized Intra-Cavity DFG, Fiber-Optic, and Quantum Cascade Laser Systems in Conjunction with Integrated Electronics for Global Studies of Climate Forcing and Response using UASs as a Partner with Satellite and Adaptive Models.

M. F. Witinski, D. Sayres, J. N. Demusz, M. Rivero, C. Tuozzolo and J. G. Anderson

In order to harness the power of UASs for in situ atmospheric monitoring of tracers such as CO2, N2O, and CH4 and as a precursor for extending detection limits to encompass sub-ppb level species, we have developed small, lightweight, single mode laser systems with co-developed integrated electronics. The laser sources are of various types including newly developed pump-enhanced difference frequency generation (PE DFG), distributed feedback quantum cascade lasers (DFB QCLs), and new types of commercially available DFB diode lasers. All are continuous wave (cw) and thermo-electrically cooled, ensuring a high instrument duty cycle in a compact, low maintenance package. The light sources are collimated with miniature aspherical lenses and coupled into a home-built astigmatic Herriott cell for detection of the various targets using direct absorption. In parallel with the optical components, we have developed integrated electrical systems for laser control, data processing, and acquisition. A prototype instrument suite is described that illustrates the importance of co-development of optical and electrical components in achieving an apparatus that is compact, fully automated, and highly capable scientifically. Although the emphasis here is on atmospheric tracers, we are already applying these technologies to spectroscopic measurements of other atmospheric species such as isotopes, free radicals, and reactive intermediates in order address several urgent science priorities defined by the NRC.

Optics Communications, Vol. 281, Issue 6, pp. 1686-1692 (2008)

Widely phase-matched tunable difference-frequency generation in periodically poled $LiNbO_3$ crystal

L.H. Deng, X.M. Gao, Z.S. Cao, W.D. Chen, Y.Q. Yuan, W.J. Zhang and Z.B. Gong

We report on the development of a laser source in the mid-infrared spectral region based on difference-frequency generation (DFG) in a periodically poled $LiNbO_3$ (PPLN) crystal. Continuously tunable coherent radiation from 2.75 to 4.78 μm was produced by optical parametric interaction between a diode-pumped monolithic continuous-wave (CW) Nd:YAG laser operating at 1.064 μm and a CW Ti:Sapphire laser tunable from 767 to 871 nm. Temperature-dependent quasi-phase-matched DFG wavelength acceptance bandwidth was studied and characterized. An empiric formula is given to estimate the phase-matched wavelength acceptance bandwidth as a function of the crystal temperature at Λ = 22.5 μm. A large frequency scan of 128 cm^{-1} (about 78 cm^{-1} above 1 μW) near 4.2 μm was achieved. The whole absorption spectrum of the P and R branches of the v_3 band of atmospheric carbon dioxide has been recorded with a single phase-matched frequency scan.

Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, Vol. 68, pp. 74-77 (2007)

A difference frequency generation spectrometer and its detection of atmospheric N_2O

Z. Cao, X. Gao, L. Deng, W.D. Chen, Y. Yuan, W. Zhang and Z. Gong

The paper reports the realization and characterization of a difference frequency generation spectrometer using periodically poled lithium niobate (PPLN) crystal. The pump and signal laser we used is a Ti:sapphire ring laser and a diode pumped monolithic Nd:YAG laser, respectively. The continuous wave (cw) infrared radiation from 2.8 to 4.8 μm has been generated. The idler radiation can be used to study fundamental absorption bands of molecules and trace gas detection. In this work, we report the detection of nitrous oxide (N2O) in atmosphere, the minimum detectable concentration of 10.9 ppbV was achieved using a Herriott cell with the optical path length of 100 m.

Applied Physics B: Lasers and Optics, Vol. 86, No. 3, pp. 497-501 (2007)

Narrow linewidth 2 μm optical parametric oscillation in periodically poled $LiNbO_3$ with volume Bragg grating outcoupler

M. Henriksson, L. Sjöqvist, V. Pasiskevicius and F. Laurell

An optical parametric oscillator using a periodically poled $LiNbO_3$ crystal and a volume Bragg grating output coupler is presented. Signal and idler wavelengths of 2008 and 2264 nm were generated from the 1064 nm Nd:YVO4 pump laser. The Bragg grating was reflecting in a narrow band around 2008 nm, creating a purely singly resonant cavity. Signal and idler linewidths of approximately 0.44 and 0.72 nm, respectively, were measured. This is a reduction of 80 and 60 times compared to when using a mirror as output coupler. A total output energy of 156 μJ was measured with 47% slope efficiency.

Optics Communications, Vol. 268, Issue 1, pp. 110-114 (2006)

Improvement to Sellmeier equation for periodically poled LiNbO3 crystal using mid-infrared difference-frequency generation

L.H. Deng, X.M. Gao, Z.S. Cao, W.D. Chen, Y.Q. Yuan, W.J. Zhang and Z.B. Gong

Improvement to the Sellmeier equation for the extraordinary index of periodically poled LiNbO3 crystal (PPLN) is reported. The equation has been improved based on a continuous tunable mid-infrared radiation realizing in a PPLN crystal using difference-frequency-

generation (DFG) and quasi-phase-matching (QPM) technique. The improved equation is suitable to estimate the QPM conditions of PPLN crystal for temperatures between 25 °C and 180 °C and mid-infrared wavelengths ranging from 2.8 µm to 4.8 µm.

- Applied Physics Letters, Vol. 89, Issue 9, 091118 (2006)
  All-fiber picosecond laser source based on nonlinear spectral compression
  M. Rusu and O. G. Okhotnikov
  The authors report the realization of an all-fiber system emitting high-quality ultrashort powerful light pulses at 1060 nm. The oscillator-amplifier system is intended for compact visible light generation via frequency conversion. Optical nonlinearity in a fiber amplifier is employed to compress the spectrum of pulses negatively prechirped in a hollow core photonic bandgap fiber. Second-harmonic generation in a periodically poled crystal is demonstrated.

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