Made Easy: CW Laser Light Widely Tunable Across the Visible

OPO technology sets new standards in wavelength coverage of commercial systems

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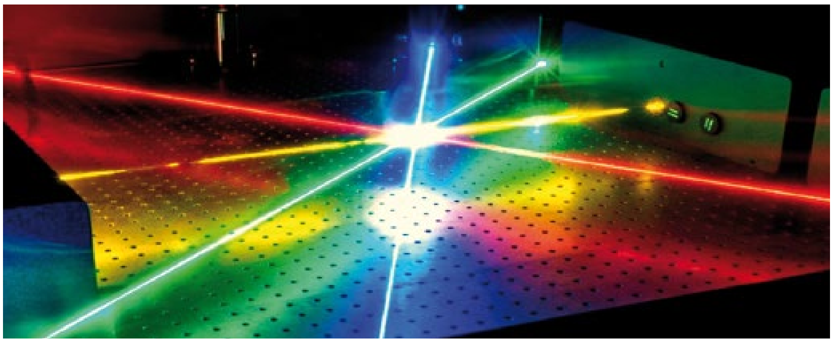
A remarkable number of photonic applications call for continuous-wave (cw) laser light that is widely tunable throughout the visible range of the spectrum. However, this spectral region remains difficult to access with conventional tunable laser devices. This is why recently commercialized sources based on cw optical parametric oscillator (OPO) technology gain market awareness – and become increasingly recognized as cost-effective and user friendly turn-key solutions.



Continuous-wave OPO technology provides laser light that is widely tunable across the visible at the push of a button.

Loosely speaking, an optical parametric oscillator (OPO) might be considered as a light source that delivers coherent radiation very much like a laser – but with two main differences between the devices [1]: First, the OPO principle is not based on stimulated emission in a gain medium (like lasers are), but on a process referred to as parametric amplification in a so-called nonlinear crystal. Second, OPOs require a coherent source of radiation as a pump source, unlike lasers, which might be pumped with either incoherent light sources or sources other than light.

That said, the huge potential of OPOs derives from their exceptional wavelength versatility, as they are in principle not limited by the wavelength coverage of suitable laser gain media [2]. They further allow output generation in all temporal regimes from continuous wave (cw) to ultrafast pulse applications. In practice, the OPO concept has been experimentally demonstrated already more than half a century ago [3], but the progress in research, development and commercialization of parametric devices has been stalled by several technical obstacles. Simply speaking, these obstacles have been easier to overcome at the high peak powers of pulsed devices, so that tunable OPOs operating in pulsed mode are nowadays readily available from a variety of commercial suppliers.

As the progress in cw OPO technology was lagging, the generation of widely tunable cw laser light in the visible range had to rely on conventional laser devices. In practice, this has been often equivalent to the necessity of changing laser gain media and resonator optics, to the handling of laser dyes, or to the acceptance of limitations in wavelength coverage. Only relatively recently, there have been exciting advances in cw OPO technology, driven both by the emergence and increasingly sophisticated design of new nonlinear crystals, as well as the increasing availability of suitable high performance solid-state pump laser sources [2]. These advances have spurred the practical realization of OPO devices with game-changing characteristics: Fig. 1 shows the first commercially available cw OPO turnkey system designed to cover the visible spectral range, an award-winning design developed by Hübner Photonics in close collaboration with the Fraunhofer Institute for Physical Measurement Techniques [4]. Based on this innovative example, the general operating principles and performance characteristics of state-of-the-art cw OPOs are discussed in the fol-

Fig. 1 Commercialized cw OPO turn-key system designed to cover the visible spectral range, as available from Hübner Photonics. The platform provides automized wavelength tunability in the range 450 – 650 nm.

Company

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Kassel, Germany

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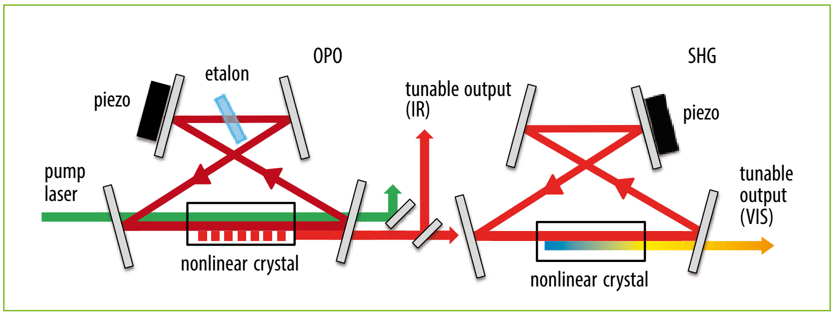

Fig. 2 Schematic beam path inside the cw OPO system shown in Fig. 1. In a first step (OPO), a 532 nm laser pumps a nonlinear crystal to generate signal and idler photons in the near infrared spectral range (900 – 1,300 nm). Wavelength selection and subsequent second harmonic generation (SHG) converts either signal or idler photons into the visible range of the spectrum (450 – 650 nm). The green arrow depicts the pump laser, dark red and light red arrows depict the signal respectively the idler beam (arbitrary assignment).

lowing. Two application highlights are presented in an illustrative manner to exemplify how the technology advances real-life experiments.

Operating principles

As mentioned above, the operation of cw OPOs puts stringent requirements on pump laser sources in terms of preferential single mode operation, noise characteristics, beam quality, and beam pointing stability. Depending on power requirements of the OPO end-user, we therefore resort to either high performance diode pumped solid state (DPSS) lasers (lower power), or to a high performance fiber laser based solution (higher power) for pumping. In either case, the wavelength of the original pump laser light is centered at 532 nm.

Fig. 2 illustrates the subsequent beam path and cascaded sequence of nonlinear optical processes in two cavities, referred to as OPO and SHG cavity, respectively. In an intuitive picture, pump laser photons are first split into pairs of photons of lower energy, commonly referred to as signal photons (in the 900 – 1,050 nm wavelength range) and idler photons (in the 1,080 – 1,300 nm wavelength range). This three-wave mixing (of pump, signal, and idler waves) is intimately linked to the second order nonlinearity of the employed nonlinear crystal. To achieve sufficient conversion efficiency, the nonlinear medium is operated inside a resonator cavity, to ensure multiple paths that increase the gain at each round trip. The employed scheme is commonly referred to as singly resonant OPO design: For a particular operational wavelength of the entire system, the OPO cavity is operated "on resonance" at either a particular signal wavelength or a particular idler wavelength, which means the effective OPO cavity length is actively stabilized to a multiple integer of that wavelength.

While keeping one of the generated waves resonantly circulating inside the OPO cavity, its counterpart can be extracted for wavelength conversion into the visible spectral range by a second nonlinear process. This step is required since – as described above – the primary OPO process generates output at wavelengths longer than those used for pumping. As illustrated in Fig. 2, wavelength conversion is achieved in a second, separate cavity by frequency doubling of the primary OPO cavity output, a process widely known as second harmonic generation (SHG). Though this configuration has been chosen from reasons of technical practicability and favorable operational stability, it should be mentioned that alternative designs, like intracavity frequency doubling, have been successfully demonstrated [1, 2, 4].

Key specifications

The clear key performance characteristic of the cw OPO platform presented here is to provide convenient access to the visible wavelength range of 450 – 650 nm. In addition, for the case the SHG generation module is not employed or switched off, the wavelength range of 900 – 1,300 nm is covered in the near infrared. Except for the so-called degeneracy gap around 532 nm (1,064 nm) of 15 nm (30 nm) width, this wavelength coverage is truly continuous and fully automized. Notably, the system design also allows access to unconverted pump light at 532 nm, as well as to unconverted portions of near infrared light used to pump the SHG cavity. Depending on the particular choice of pump laser, output powers of up to 800 mW can be achieved (power tuning curves not shown here for the sake of brevity).

Not least due to an integrated Pound-Drever-Hall (PDH) frequency stabilization scheme, the system delivers high quality cw output with typical linewidths of <500 kHz corresponding to typical coherence lengths well above 100 m throughout both the visible and the near infrared tuning range. Thereby, a long term frequency stability of <150 MHz over hours is routinely achieved at typical lab conditions. It should be emphasized that for applications with highest demands, the performance characteristics can be even further improved by operating the system in closed-loop mode, i.e. in conjunction with an external wavelength measurement device (wavemeter) and an optionally available software package. As illustrated in Fig. 3, in this operation mode, the achievable long term stability essentially approaches the measurement resolution of the external wavemeter device itself.

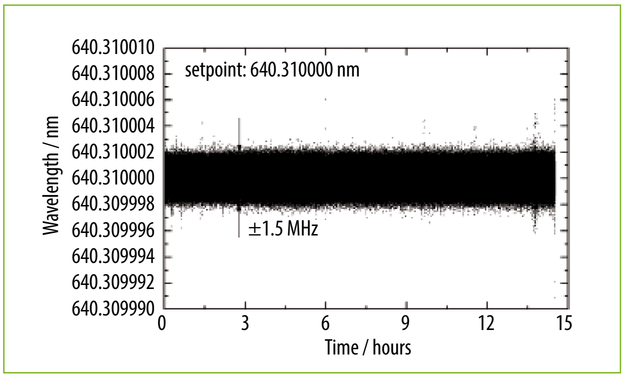

Fig. 3 Long-term frequency stability of the cw OPO output in closed-loop operation. Employing a software module in conjunction with a high performance wavemeter, a frequency stability of ±1.5 MHz over hours is achieved.

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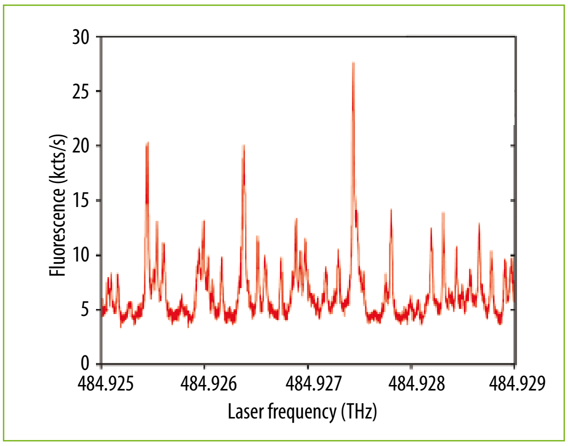

Fig. 4 Excitation wavelength dependent fluorescence intensity of dibenzanthanthrene (DBATT) molecules hosted in a naphtalene crystal at cryogenic temperature [5]. The spectrum is recorded for a modehop-free scan over 4 GHz at a center wavelength of 618 nm.

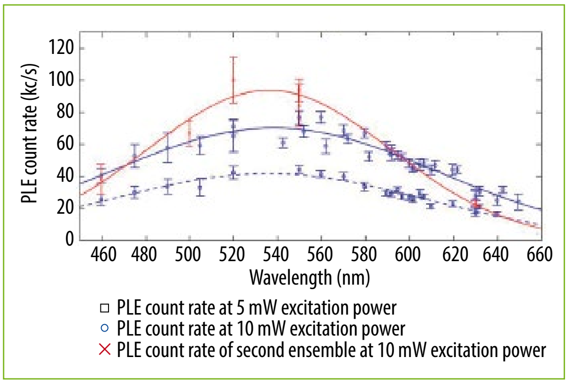

Fig. 5 Photoluminescence excitation (PLE) spectra of color center ensembles in diamond at room temperature [6]. The data is recorded at different excitation powers for a series of excitation wavelengths between 460 and 650 nm.

Real-world performance

Last not least, the performance shall be illustrated on the basis of two experimental examples. The particular systems under study clearly are to be distinguished in terms of the underlying photophysics, but the experimental approaches do share some obvious similarities, by simultaneously exploiting the narrow linewidth, decent output powers, and wide tunability of cw OPOs.

Fig. 4 shows the fluorescence excitation spectra of single molecules in a solid-state crystal at cryogenic temperatures [5]. Under such conditions, individual molecules can be regarded as nearly ideal two-level systems with natural linewidths in the range of typically 10 – 50 MHz. Due to imperfections of the local surrounding crystal matrix, their transition energies are inhomogeneously distributed over a much wider spectral range. As can be perceived from the experimental data shown in Fig. 4, the measurements unambiguously reveal several narrow spectral features within a scanning range of 4 GHz, corresponding to individual molecules. As outlined above, it is further possible to lock the OPO wavelength in closed-loop mode to a selected single-molecule resonance for investigating its properties on an individual level.

Fig. 5 shows a series of photoluminescence excitation spectra of so-called color centers in diamond at room temperature [6]. Color centers are local defects (vacancies) in the diamond lattice related to impurities, and have gained considerable attention over the last decade – not least as potential single photon emitters, which are the heart of many promising quantum technologies such as quantum computing and quantum cryptography. Clearly, understanding the internal energy level structure is of fundamental importance for future applications. The results shown in Fig. 5 are part of a recently published study on the level structure of a novel class of vacancy centers in diamond [6]. Their spectroscopic characterization over a broad wavelength range from 460 – 650 nm at sufficiently high excitation intensities has been enabled by cw OPO technology.

Outlook

Their unique characteristics make cw OPOs highly competitive alternatives to conventional lasers and related technologies for the generation of widely tunable cw radiation. The characterization of single-photon emitters and alike is thereby only a subset of applications, where OPO technology permits to conveniently carry out measurements that would have been otherwise hampered by the technical complexity of suitable sources, or even the lack thereof. An exciting variety of further applications, ranging from production of diffractive optical elements (DOEs) for holography, over scanning near field optical microscopy (SNOM), to state-of-the-art methodologies in Raman scattering, is anticipated in view of first encouraging results.

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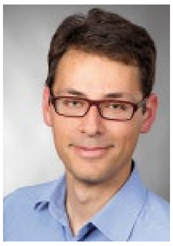
Jaroslaw Sperling is sales manager for Hübner Photonics. He joined the company in 2016, bringing in his passion and experience gained in various sales and marketing related roles across photonics research and industry. With a solid background in laser spectroscopy, he holds a PhD in physical chemistry from the University of Vienna.



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