Tunable Laser Light Sources Advance Quantum Research

Optical parametric oscillators offer a competitive alternative to conventional lasers for quantum nanophotonics.

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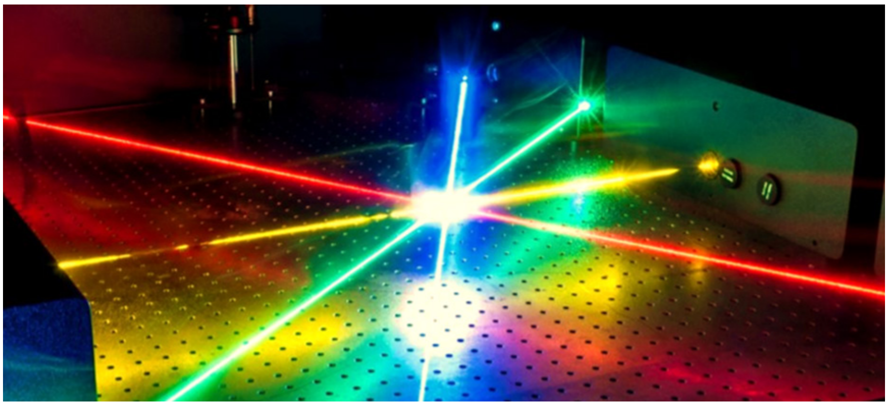
A remarkable number of photonic applications call for continuous-wave (cw) laser light that is widely tunable throughout the visible range of the spectrum. However, this spectral region remains difficult to access with conventional tunable laser devices. This is why recently commercialized sources based on cw optical parametric oscillator (OPO) technology have gained market awareness - and become increasingly recognized as cost-effective and user friendly turn-key systems. The basic operating principles of such cw OPOs is discussed followed by an illustratives example of how these OPOs help researchers analyse nitrogen vacancy (NV) centers in diamond.



OPO technology provides laser light that is widely tunable across the visible spectral range. Figure courtesy of Jens Kiessling (Fraunhofer Insitute for Physical Meaurement Techniques).

Principles of OPOs

Optical parametric oscillators (OPOs) might be considered as light sources that deliver coherent radiation very similar to lasers – but with two main differences between the devices [1]: First, the OPO principle relies on a process referred to as parametric amplification in a so-called nonlinear optical material, rather than on stimulated emission in a laser gain medium. 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.

In the basic scheme common to OPOs and other optical parametric devices is the process can be perceived as splitting of an incoming pump photon of high energy into two photons of lower energy, the latter usually referred to as signal and idler photons, respectively. It is esential to note that the overall process is subject to the conservation principles of photon energy and photon momentum (phase matching condition), but otherwise does not underlie further fundamental restrictions, at least in theory. The huge potential of OPOs thus derives from their exceptional wavelength versatility, as they are in principle not limited by the wavelength coverage dictated by the energy levels and suitable transitions in a laser gain medium.

In practice, the OPO concept has been experimentally demonstrated already more than half a century ago [2], but the progress in development and commercialization of turn-key devices has been stalled substantially by several technical obstacles [3]. 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 have become readily available from a variety of suppliers. Only relatively recently, there have been comparable advances in continuous-wave (cw) OPO technology [3], which have spurred the development of commercial systems.

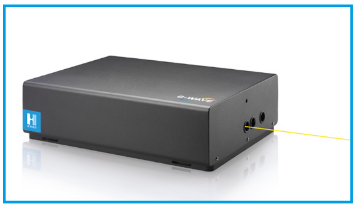


Fig. 1 Commercialized cw OPO turn-key system designed to cover the visible spectral range, as available from Hübner Photonics. The platform provides automized wavelength tunability in the range 450 –650 nm.

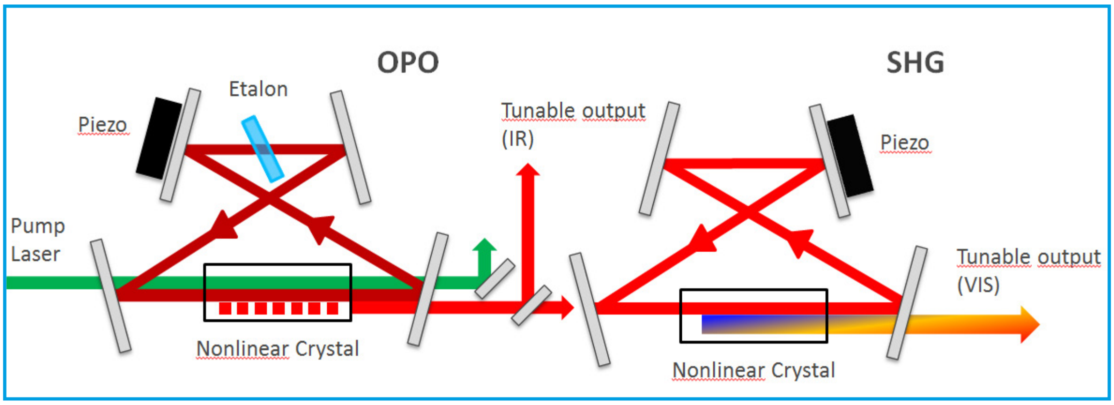


Fig2. Schematic beam path inside a commercial CW OPO system (see reference 4). In a first step (OPO), a 532-nm laser pumps a nonlinear crystal to generate signal and idler photons (900 to 1300 nm). Wavelength selection and subsequent second-harmonic generation (SHG) converts either signal or idler photons into the visible range of the spectrum — 450 to 650 nm. Pump laser beam (green arrow); signal beam (dark red); idler beam (arbitrary assignment) (light red). Courtesy of Hübner Photonics.

Design Considerations

While OPO technology appears to be ideally suited for generating tunable cw laser light across arbitrary wavelength ranges, one must keep in mind that the OPO process itself will always generate output at wavelengths that are longer than those used for pumping. Consequently, OPO devices operating across the visible spectral range do either require UV pump sources, or, alternatively, need to employ additional frequency conversion stages. As of today, only the latter approach has been proven to be technically practicable and operationally stable in commercial turn-key systems.

For illustration, the essential building blocks of a tunable cw OPO [4], designed to cover the visible range, are shown in Figure 2. In essence, the operational principle relies on a cascaded sequence of nonlinear optical processes within two cavities, referred to as OPO and SHG cavity, respectively. As outlined above, pump laser photons are first split into pairs of photons of lower energy (signal and idler). The particular OPO scheme employed is commonly referred to as singly resonant OPO cavity design: For a certain operational wavelength of the entire system, the cavity is operated “on resonance” at either a particular signal wavelength, or a particular idler wavelength. Thereby, a precisely moveable stack of periodically poled nonlinear crystals allows for broad wavelength coverage. At a particular wavelength selection, a crystal layer with a suitable poling is automatically selected and its poling period fine-adjusted through a temperature control loop. At the same time, the effective OPO cavity length is actively stabilized to a multiple integer of the selected operational wavelength. While circulating one of the generated (signal or idler) waves resonantly inside the OPO cavity, its counterpart can be extracted for wavelength conversion into the visible spectral range by another nonlinear process. As illustrated in Figure 2, this wavelength conversion takes place 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 is technically practicable and provides favorable operational stability, it should be mentioned that alternative designs, like intra-cavity frequency doubling, have been successfully demonstrated in the lab.

Key specifications

In Figure 2, the typical CW OPO device encompasses continuous tunability across the range of 450 to 650 nm, delivery of high-quality laser light output with a typical linewidth of <500 kHz, and generation of output powers in the range of several hundreds of milliwatts. Notably, long-term frequency stabilities as good as ±1 MHz over 10 hours have been demonstrated when operating CW OPOs in closed-loop mode, in conjunction with external wavelength measurement devices[4] (Fig 3.). Though the particular CW OPO design shown in Figure 2 has been optimized for pump laser wavelengths of 532 nm (in its commercialized version), the layout is generic enough to accept different pump wavelengths. These can be exploited to shift the overall wavelength coverage while keeping the same design principle.

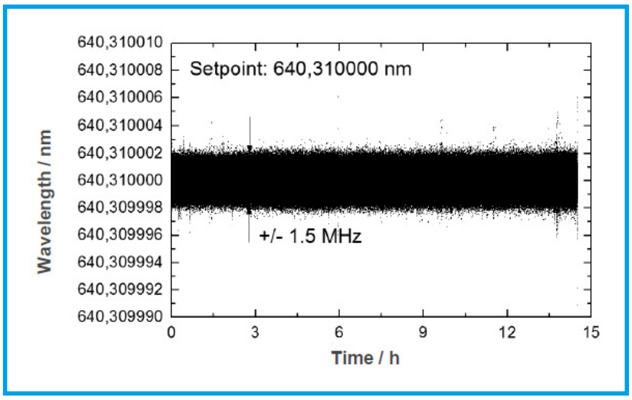


Fig. 3 Long-term frequency stability of the cw OPO output in closed-loop operation. Employing a software module in conjunction with a high performance wavemeter, a frequency stability of ±1.5 MHz over hours is achieved.

Real world performance

Not surprisingly, the sweet spots for implementing CW OPO technology are experimental settings that require narrow linewidths and significantly benefit from the accessibility of a wide tuning range, but are not too demanding in terms of output powers. Several examples are described below in an illustrative manner. Notably, the particular systems presented here are to be clearly distinguished in terms of the underlying physical phenomena that determine their spectroscopic signatures. However, in a broader perspective, all of the experiments are sensitive probes of nanoscale factors governing the light-matter interaction.

Fig. 4 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].

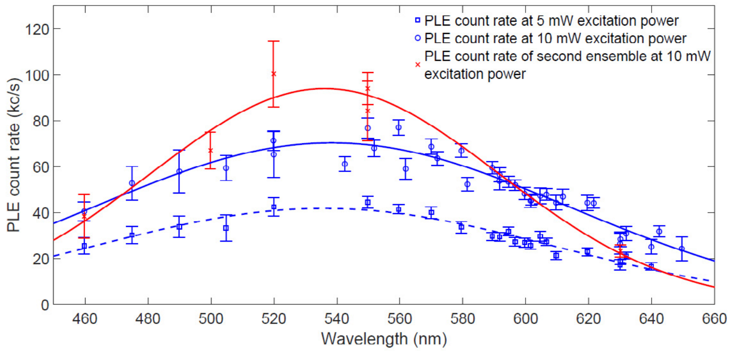


Fig. 4 Photoluminescence excitation (PLE) spectra of a color center ensembles in diamond at room temperature (see reference 7). The data is recorded at different excitation powers across a series of excitation wavelengths between 460 and 650 nm. Blue squares and circles show measurements at 5 mW and 10 mW (respectively) of excitation power of one and the same ensemble. Red I-bars refer to measurements at 10-mW excitation power of a second ensemble. kc/s: kilocounts per second. Courtesy of Alexander Kubanek/Hybrid Quantum Systems Group, Ulm University.

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-theart methodologies in Raman scattering, is anticipated in view of first encouraging results.

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At HÜBNER Photonics, we not only make game-changing lasers, but also rethink all kinds of other technologies including terahertz imaging and high-frequency radar. Since 2015, our portfolio has been further reinforced by the acquisition of Cobolt, a world leading manufacturer of high performance lasers for analytical instrumentation. Together, we unite proven corporate values with innovative ideas and top-notch technologies for the whole electromagnetic spectrum.

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