CW laser light tunable from blue to red: OPOs pave the way

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Optical parametric oscillators (OPOs) are widely tunable and thus turn out as very flexible light sources. Until recently, OPOs for the visible frequency range were commercially available as pulsed systems only. In this article, two concepts are presented, which pave the way into the visible spectrum for continuous-wave OPOs.

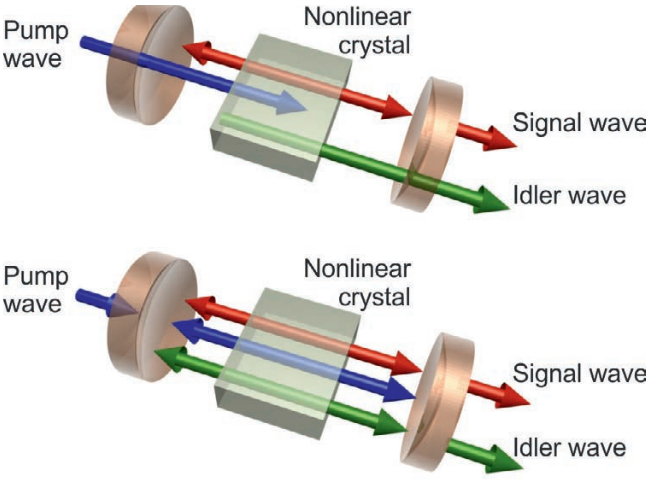

Figure 1: Schematic setup of continuous-wave optical parametric oscillators. The incoming pump wave is converted into signal and idler wave within a nonlinear crystal. By choosing the mirror-coatings correctly either single (top) or multiple waves (bottom) are resonantly enhanced

1 What are optical parametric oscillators?

Only a few years after the realisation of the first laser by Theodore Maiman in 1960 [1], the first optical parametric oscillator (OPO) was demonstrated [2]. Today, OPOs enable a broad variety of applications, such as molecular spectroscopy, photo chemistry, quantum optics, and trace gas analysis.

An OPO converts monochromatic light so that it can become widely tunable, employing an optically nonlinear process. The coherence properties of the initial light are preserved. This OPO process divides an incoming pump wave with the frequency ν_p into two waves: a signal wave with the frequency ν_s and an idler wave with the frequency ν_i. Here, the generated frequencies are always smaller than the initial one. Two conditions need to be fulfilled, the frequency condition

$$\nu_\mathrm{p} = \nu_\mathrm{s} + \nu_\mathrm{i} \qquad \text{(Eq.1)}$$

as well as the phase matching condition:

$$\vec{k}_\mathrm{p} = \vec{k}_\mathrm{s} + \vec{k}_\mathrm{i} + \Delta\vec{k} \qquad \text{(Eq.2)}$$

Here, k_p, k_s and k_i are the absolute values of the wave vectors $k_x = 2\pi\, n_x/\lambda_x$ with n_x being the wavelength-dependent refractive index. Both equations can be interpreted as energy and momentum conservation when using the photon description of light. In this context, the parametric process can be seen as splitting of the pump photon.

These two conditions fully determine the frequencies of both signal and idler photons and no further restrictions come into play regarding the tunability. Thus, in principal, photons with every desired frequency can be generated as long as this resultant frequency is lower than that of the pump photon (Eq.1). OPOs are therefore continuously tunable over the entire transparency range of the nonlinear medium employed. This illustrates one of the major advantages of OPOs in comparison with lasers whose emission frequency is determined by discrete transitions between energy levels.

For example, phase matching can be achieved by using the natural birefringence of a nonlinear medium, e.g. in a lithium niobate crystal – in this case $|\Delta\vec{k}| = 0$ holds. Another possibility is the so-called "quasi phase matching". Here, the nonlinear material is structured in such a way that the orientation of its crystal structure alters with a periodicity of Λ, fulfilling Eq.2 with $|\Delta\vec{k}| = 2\pi/\Lambda$. By varying the temperature and/or the period length Λ, one can influence the phase matching condition, and thus deliberately choose the frequencies ν_s und ν_i. This enables tuning of the emitted wavelengths over a large spectral range.

For the parametric processes to run efficiently, the nonlinear medium is operated as an oscillator in a cavity. Such cavities resonantly enhance one, two, or even all three interacting waves. **Figure 1** shows two of these resonator types in a standard configuration with mirrors.

OPOs can emit either pulsed or continuous-wave (CW) light. Although the first OPO was a pulsed device, the first CW system was realised only three years later [3]. Notably, the initial pump power must be high enough to overcome the oscillation threshold. This can be achieved relatively easy in pulsed devices because of the high peak powers, but remains challenging in CW systems.

2 CW laser light sources

In general, the linewidth of CW laser light can be much smaller than the one of pulsed light. The bandwidth of pulsed systems is fundamentally limited by the inverse of their pulse duration, e.g. 10 ns pulses lead to a linewidth of at least 100 MHz. Thus, certain applications can take place with CW light only. Few CW laser light sources exist for the visible spectral range that can be tuned (**figure 2**).

One prominent example is the titanium-sapphire laser, which emits tunable light with wavelengths from red to the near-

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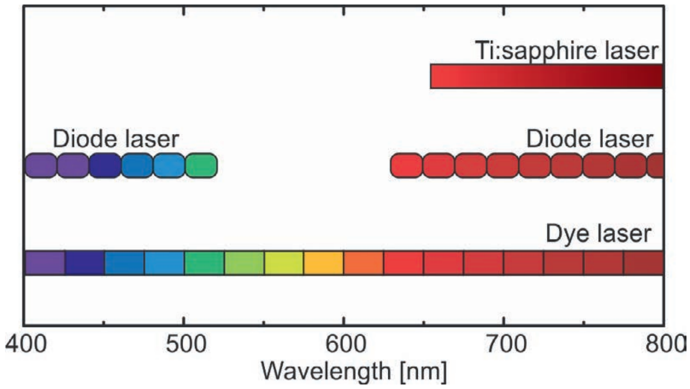

Figure 2: Continuous-wave sources currently available, emitting tunable light in the visible frequency range. So far, no light source covers the entire regime with just a single system. Even in dye lasers, each dye only provides a tuning range of typically 20-50 nm

infrared. However, the rest of the visible spectrum remains unreached. Laser diodes operate in several spectral ranges – but not in the yellow regime. In addition, the light of each diode can only be tuned over several nanometers, thus many diodes have to be used in order to cover large parts of the spectrum. Dye lasers are another type of tunable light source. Unfortunately, these systems also have several disadvantages: to cover the entire visible spectrum, the dyes have to be exchanged. Besides this complicated procedure, the dyes employed are mostly toxic, difficult to handle, and age quickly.

In contrast to alternatives, OPOs are ideally suited for providing continuous-wave light over large spectral ranges. To date, the only commercially available OPOs operate as pulsed systems for the visible spectrum. Yet which OPO challenges need to be overcome for CW systems? Since the pump frequency always has to be higher than the generated frequencies, one would have to use an ultraviolet (UV) pump laser for reaching the visible spectrum. However, such a pump source with sufficient output power of CW light is not available.

To exploit the OPO principles, different approaches can be pursued. For example, UV pump lasers can be avoided if the OPO output at infrared wavelengths can be subsequently converted into visible light by using another nonlinear process. Yet another different approach aims at reducing the threshold of the nonlinear process, enabling the use of low power sources for UV light. In the following, these two concepts will be presented in detail.

2.1 Combination with frequency doubling

Frequency doubling or second harmonic generation (SHG) is a nonlinear process by which a wave with twice the frequency of the one of the initial pump wave is created. While OPOs generate light at frequencies lower than those that pump them, a combination with SHG leads to higher frequencies. A cascade of these two processes – OPO and SHG – is thus well suited for generating continuous-wave light tunable over the entire visible spectrum.

We have chosen a two-step-process: At first, a conventional OPO cavity formed by mirrors is pumped with green laser light. This primary process creates continuously tunable waves with frequencies in the near-infrared. These OPO output waves then serve as pump input waves for the SHG-process, in which their frequencies are converted into the visible. In 2002, such a principle could be demonstrated for the first time using two distinct resonators for the two different nonlinear processes [4]. In our system, the SHG-crystal is integrated directly in the OPO-cavity and is able to double the frequencies of both signal and idler waves. This enables continuous tuning from blue to red. To date, our OPO-SHG system covers 450 to 650 nm without any gaps (**figure 3**). By translating the nonlinear crystal – thus using different period lengths – and by changing the crystal temperature, different wavelengths can be realised. The desired wavelength can be selected at the computer and the device automatically adjusts itself in less than a minute with a wavelength accuracy of 1 nm. The tuning range is currently limited by the mirror-coatings. The pump powers necessary are in the order of Watts and can thus create high output powers of about 100 mW.

Based on the research of these nonlinear effects, a prototype is now in the process of being commercialised in cooperation with an industrial partner.

2.2 Whispering gallery resonators

So-called whispering gallery resonators (WGR) help reduce the threshold of nonlinear processes tremendously. WGRs comprise small discs with diameters in the millimeter range or lower. Light can be guided via total internal reflection at the circumference of these discs. In this scheme, reflection losses are minimised over the entire transparency range of the medium.

WGRs combine a small mode volume with ultra-high quality factors, letting the light circle within the disc for several million times [5]. The high number of cycles also leads to high intensities inside the resonator, making the observation of nonlinear processes at low input pump powers possible. WGRs are thus ideal for CW-based OPO systems because they provide several advantages in comparison with mirror-cavities: WGRs are small, intrinsically mechanically stable and do not have to be adjusted.

Figure 4 schematically illustrates a WGR-OPO. Here, the pump wave is coupled into the resonator via a prism. This prism is also used to extract both signal and idler waves from the resonator. Such a system simultaneously provides resonant enhancement for pump, signal and idler waves.

Two major aspects are necessary for building such WGR-OPOs: the production of a

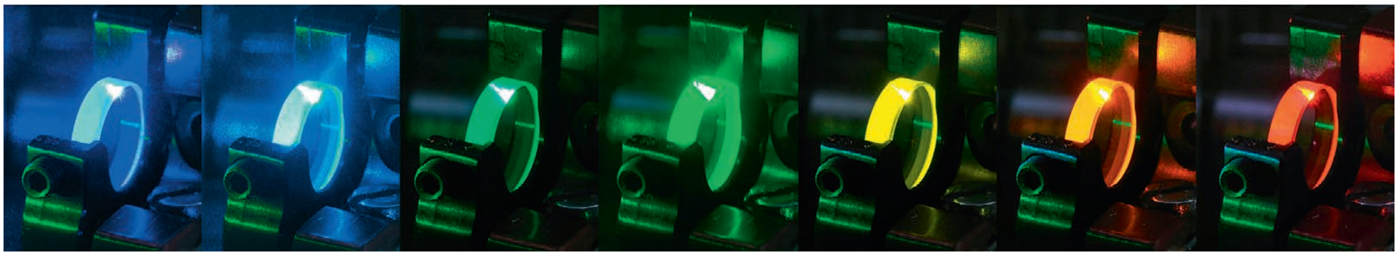

Figure 3: Part of the optical parametric oscillator generating continuous-wave light via intra-cavity frequency doubling. The visible spectral range can be covered completely from blue to red

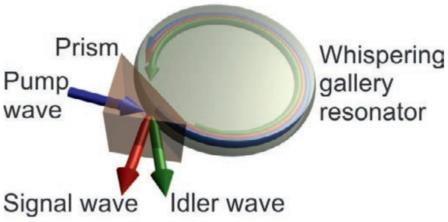

Figure 4: A pump wave is coupled into a whispering gallery resonator using a prism. This pump wave generates signal and idler wave. All three interacting waves are resonantly enhanced

low-loss, monolithic resonator and the fulfillment of the phase matching condition. WGRs, made out of crystalline materials, are typically constructed in three steps: At first, a cylindrical body is drilled out of the crystal. In a second step, the outer rim is suitably shaped on a lathe. Finally, the surface roughness is reduced to a few nanometres by polishing the resonator. In order to fulfill the phase matching condition two concepts known from standard mirror resonators have been applied: birefringence [6] as well as quasi phase matching [7].

Figure 5 shows the setup of a WGR-OPO. It is pumped by blue light and generates red light with wavelengths tunable from 707–865 nm as well as 1120–1575 nm by varying the crystal temperature [8]. The diameter of this resonator is only 2 mm.

The input powers necessary can be very small, as demonstrated in **figure 6**. Here, the OPO process sets in at only 4 µW and reaches its maximum efficiency of 13% at a pump power of 20 µW. This value corresponds to a quantum efficiency of 17%. OPOs with pump thresholds this small are ideally suited for quantum mechanical experiments because lasers with low output power, which can now serve as pump sources, typically have very low noise levels. Currently, the maximum output power in WGR-OPOs is limited to several milliwatts because of instabilities occurring due to the high intensity enhancement inside the resonators.

In the near future, the efficient generation of CW light should be accomplished over the entire visible spectrum in WGRs, realising compact and continuously tunable light sources.

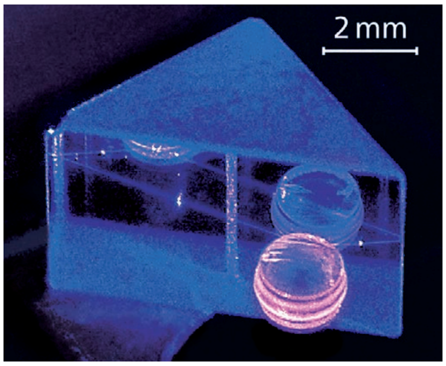

Figure 5: Blue light is sent into a whispering gallery resonator and converted into light tunable in the red spectral regime. One can clearly see the red ring of the circulating signal wave close to the coupling prism

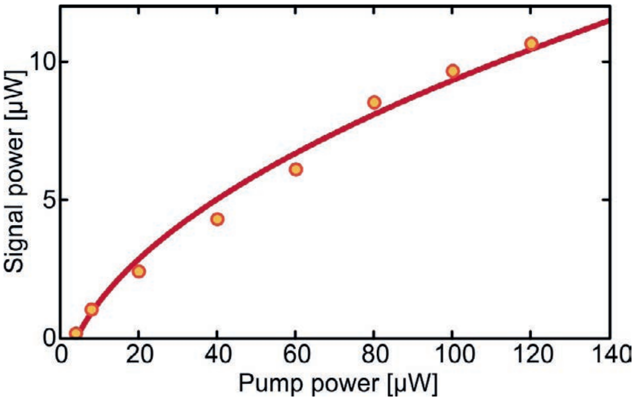

Figure 6: Signal power at 590 nm of a whispering gallery resonator plotted against the pump wave of the optical parametric process. Conversion via the nonlinear process sets in at only 4 µW of pump power

3 Conclusion

To generate tunable laser light in the visible spectral range with high output powers, one can use a combination of OPO and SHG in standard mirror-cavities. In contrast, WGRs are ideally suited as compact light sources. Here, very small pump powers are sufficient for starting nonlinear processes that can convert frequencies into the visible range. Their maximum output power is currently limited to a few milliwatts.

Both concepts show that continuous-wave OPOs have already proven viable in the visible spectrum.

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