# PURCHASING
# a femtosecond oscillator

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What is the purpose of a femtosecond oscillator? The answer cannot be a very short one, in light of the multiple applications developed around this type of instrument, in the fields of microscopy, metrology, not to mention micro-machining or surgery, and including applications in the field of fundamental physics.

Femtosecond laser systems are almost as varied as their applications. So before choosing such a system it is important to carefully assess the determining parameters for the experiments which are to be performed. The first question one should ask oneself is, naturally: which oscillator should I choose? Although the oscillator is sometimes integrated in an amplified chain and its characteristics do not impact the overall performance of the global system, some of its specific features should be considered. The operating range of femtosecond oscillators is quite broad in terms of wavelength (typically in the red and near-infrared ranges), of duration (from several hundredths of fs to sub-10 fs), of repetition rate (tens of MHz to several GHz) and of energy (nJ to µJ). In addition to these criteria it must be borne in mind that they are not all mutually compatible, and that many options can be added, such as carrier envelope phase stabilisation (CEP), wavelength extension by non-linear effects, pulse picking, etc. We shall try to shine some light on these matters by providing – non-exhaustively – a few ways to approach the problems involved in purchasing one.

## Technical analysis of femtosecond oscillators

For a good understanding of the anatomy of a femtosecond oscillator, let us start from this truism: it is a laser cavity designed to produce ultra-short pulses. To achieve this, three functions must be inserted in the cavity: laser gain, clearly, a non-linear effect of the saturable absorbent type (in the widest sense), to favour the pulse regime, and control of group velocity dispersion to guarantee satisfactory propagation and stability of the ultra-short pulses in the cavity. Let us now analyse these various points to assess their impact on the product.

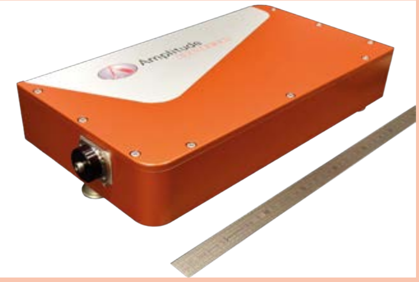
**Figure 1.** Photograph of industrial fs oscillator, based on a crystal doped with ytterbium (photographic credit Amplitude Systemes).

The primary purpose of the laser material is to amplify, but it is responsible for most of the characteristics and the potentials of the femtosecond laser. It is thus the choice of the laser material which will impose the central wavelength and the tuning range. It will also determine the accessible minimum duration[1]. The choice of a fibre-based oscillator will also be an important choice in terms of ease of integration and cost. From another standpoint, crystal oscillators enable higher energy levels to be obtained. Finally, the choice of the material will (or will not) allow the use of direct pumping by power laser diode, allowing lasers of high average power, which are efficient and less expensive.

The choice of the non-linear effect which will play the role of saturable absorber is important above all for the system's reliability and reproducibility. From this standpoint it is generally preferable to choose Kerr lens mode-locking (KLM) or locking by the semiconductor-based saturable absorber (SESAM), with the disadvantage that the first does not operate for all types of materials (e.g. fibres), and that the second tends to restrict the spectral bandwidth.

Dispersion compensation can be accomplished using prisms or mirrors for crystal systems, and using gratings or dispersion-controlled fibres for fibre-based systems. With a view to simplification and greater compactness, systems with prisms or gratings are sold increasingly rarely. The cavity[2], for its part, will determine the repetition rate of the oscillator. It is sometimes advantageous to choose low frequencies (20-40 MHz) to favour pulse energy and/or reduce the constraints for a possible pulse picker.

The choice of oscillator must be made in light of the fact that extensions or options can be associated with it. These are a few examples:

- The repetition rate can be reduced by adding an acousto-optical or electro-optical modulator. Even if the modulator's efficiency is generally satisfactory, this decimation greatly reduces the average power and often implies post-amplification.
- Wavelength extension can be accomplished by adding a non-linear module. Let us cite, for example, access to the visible wavelengths by generation of second or third harmonics (SHG, THG). The use of optical parametric oscillators (OPO) after the lasers is also often advantageous. Indeed, even if the energy is generally reduced by an order of magnitude the use of OPOs and of SHG allows access to wavelengths covering several octaves.
- Dispersion compensation modules can be added to the oscillators' outputs to pre-compensate for group velocity dispersion in the analysed samples (e.g. in microscopy).
- Finally, femtosecond lasers can also include control systems which finely tune the optical length of the cavity to create new functions. This is useful, for example, to guarantee synchronisation of the sequence of pulses (synchrolock) or to stabilise the envelope phase (carrier-envelope phase, CEP). As shown by *figure 2*, this type of control greatly increases the complexity of the oscillator's architecture.

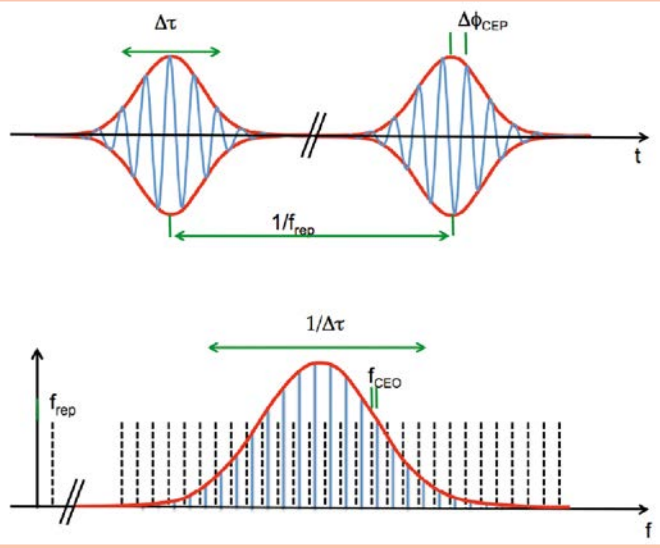

**Figure 2.** Time-frequency correspondence. Definition of repetition frequencies frep, of the offset between the carrier and envelope fCEO (CEO carrier envelope offset), and the CEP (carrier-envelope phase) of the laser.

## The major families of oscillators

Commercial femtosecond lasers can, globally, be divided into three major categories according to the gain material, or then into two types of architecture (crystal-based or doped fibre-based).

### Crystal-based femtosecond lasers

Systems based on sapphire doped with Ti (Ti:Sa), which emit between 700 and 1100 nm (with more or less spectral tuning), are very dominant in the niche of 7-30 fs ultrafast lasers. This constitutes their main benefit. The oscillators' average power is typically between 100 mW to few watts. Their main disadvantage is their pumping in the green, which leads to complex and expensive systems. Mode-locking uses KLM. These lasers are very widely used in non-linear microscopy (even though they are tending to be replaced by Yb+OPO laser systems), or to seed high peak power laser chains (TW and PW lasers). Ti:Sa oscillators can be stabilised in CEP and can be used in the field of metrology.

For their part, the main advantage of crystal lasers doped with $Yb^{3+}$ is that they are able to supply very

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[1] More technical details will be found on the subject in *New laser crystals for the generation of ultra-short pulses*, Comptes Rendus de l'Académie des Sciences, Recent advances in crystal optics, C.R. Physique 8 153-164 (2007) and in *Systèmes femtoseconde, optique et phénomènes ultra-rapides*, pp 13-49.

[2] By adjusting its length and the pulses roundrip time.

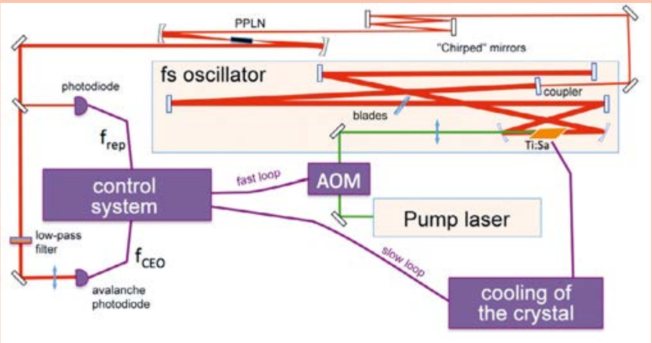

**Figure 3.** Example of CEP-controlled Ti:Sa laser (CEP: carrier-envelope phase) (source Rainbow of Femtolaser/SpectraPhysics). The Ti:Sa oscillator is stabilised using two control loops. The PPLN non-linear crystal enables a frequency difference to be made between the two extreme parts of the spectrum, which are then made to interfere with the original spectrum to measure fCEO (CEO: carrier-envelope offset). AOM: for acousto-optical modulator.

high average power levels (up to several tens of W) and energy levels (up to µJ) since they are pumped directly by diodes. However, their duration generally remains in the range of 100-800 fs and their emission is restricted to around 1030 nm. These systems generally use a SESAM. Finally, Yb-based oscillators are *de facto* compatible with Yb amplifier technology, which allows record average powers and efficiencies.

## Fibre-based femto lasers

The advantage of fibre lasers is that they can prevent any propagation in free space, making these systems extremely robust to external conditions. They can also be coiled in cassettes and compacted. To lock the modes in phase, they generally use SESAMs, or alternatively take advantage of the strong non-linear effects in the fibres (typically non-linear polarisation rotation). The main disadvantage of fibre-based oscillators is that they are limited in terms of energy/power by the fact that the laser is confined in the small fibre core. However, it is possible to add amplification modules to increase power performance without greatly increasing complexity (cf. *Fig. 4*).

The two main technologies of fibre-based oscillators are those based on fibres doped with Yb or Er. Lasers with Yb fibre typically emit in the range of 1030 nm for durations of 200 to 300 fs with several tens of mW. They are widely used to seed very high power fibre-based systems. Lasers with Er fibre enable durations of 30 to 100 fs to be obtained at around 1550 nm (telecoms wavelength). Their robustness makes them advantageous for low-noise systems and/or CEP, with applications in particular in the field of metrology.

## What should I choose?

With all these criteria it can be helpful to highlight several characteristics in order to help to choose the "right" fs oscillator for a given application.

The duration, which is the eponymous characteristic of femtosecond lasers is, paradoxically, the parameter which is least used directly, and indeed it is often its relationship with the peak power or the broad spectrum which is most important. Oscillators' durations can range from a tenth to several hundreds of fs. Sub-20 fs durations can be essential if a very high time resolution is sought, or when one is interested in phenomena sensitive to the electric field (e.g. generation of attosecond pulses). However, duration has a cost in terms of complexity, and maintaining it is a difficult challenge. Attention will therefore be paid to this parameter in oscillators integrated in ultrafast chains, always bearing in mind that sometimes it is possible to strive too hard to achieve perfection[3]. A few applications in which duration must be taken into account are pump-probe experiments, experiments involving time-resolved spectroscopy or luminescence, metrology of semiconductor wafers, or photo-acoustics, THz or attosecond experiments, etc.

Peak power is probably the primordial parameter of femtosecond lasers since it is behind non-linear optics applications. This parameter is closely related to energy[4]. With typical energy values of one nJ to one µJ, this gives peak power values of between 100 W and 100 MW, but generally they are around

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[3] For example, for applications such as micro-machining or surgery, durations of several hundreds of fs are sufficient to guarantee athermal ionisation.

[4] Peak power is the ratio of energy to pulse duration.

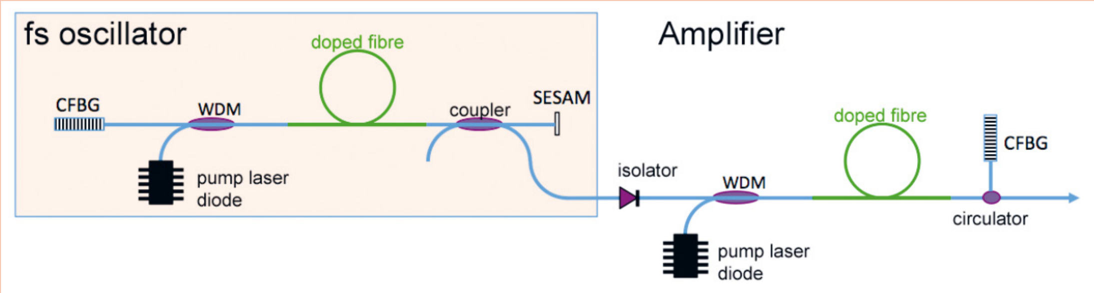

**Figure 4.** Example of fibre-based amplified laser without alignment, which is ultra-compact. The CFBG (chirped fiber Bragg grating) controls dispersion. WDM (wavelength division multiplexing) allows multiplexing of the pump and the laser.

one MW. The peak power values can be increased in amplified systems up to several GW for high-frequency systems (typically fibre-based systems), or to one PW, with crystal-based record systems. There are nonetheless applications for which oscillator output energy is sufficient, such as non-linear microscopy (2PEF, CARS, etc.) or generation of THz.

Since lasers' spectra are inversely proportional to pulse duration, the spectra of ultrafast lasers are the broadest. This bandwidth can be used advantageously in certain cases: for frequency combs in which the stabilisation system (CEP and CEO) requires extended spectra, or for optical coherence tomography (OCT) applications for axial resolution problems.

The spectral range of the laser (colour and tuning) is also a parameter which can be important, in particular to correspond to the spectra of the fluorophores (in particular in non-linear microscopy), or simply to be suitable for amplifiers.

Finally, repetition rate is a parameter which is acquiring increasing importance when choosing oscillators, in particular due to the appearance of systems doped with Yb ions, which allow a very great gain in terms of average power and recurrence of the processes[5]. With oscillators, it should be noted that low frequencies are of greater interest for systems requiring a pulse picker, and high frequencies in order to have a broad frequency comb.

## Conclusion

There is a wide choice of different femtosecond oscillators. It is therefore of interest to examine certain properties which are more critical than others, depending on the application. We have shown a number of important – and not exclusive – parameters. It should also be noted that stability, reliability and compactness are also essential for many applications. ■

## GUIDE TO OSCILLATORS

| SUPPLIER | MAKES | PRODUCTS | CONTACT |
|---|---|---|---|
| Coherent | Coherent | Ti : Sa, Yb | Jean-Luc Tapié - jean-luc.tapie@coherent.com<br>+33 1 80 38 10 11 / +33 6 09 17 40 72 |
| Microcontrole<br>Spectra Physics | Spectra -Physics<br>High-Q | Ti : Sa, Yb | Dalila Ait-Amir - dalila.aitamir@newport.com<br>+33 1 60 91 68 45 |
| Amplitude Systemes | Amplitude Systemes | Yb | Vincent Rouffiange - vrouffiange@amplitude-systemes.com<br>+33 5 56 46 40 62 |
| Acal Bfi | Ekspla<br>Onefive | Fibre Er<br>Fibre Yb | Dadi Wang - dadi.wang@bfioptilas.com<br>+33 1 60 79 59 84 |
| Optoprim | Ligthconversion<br>Fianium<br>M-Squared | Yb<br>Ti:Sa<br>Ti:Sa | François Beck - fbeck@optoprim.com<br>+33 1 41 90 33 77 |
| Opton Laser | Advalue Photonics<br>Laser Quantum<br>Toptica | Fibre Er<br>Fibre Yb | Vincent Aubertin - vincent.aubertin@optonlaser.com<br>+33 1 69 41 04 05 |
| Novae | Novae | | Nicolas Ducros - n.ducros@novae-laser.com<br>+33 6 58 09 12 89 |
| KMLabs Lasers | KMLabs Lasers | | Kapteyn-Murnane Laboratories Inc., USA<br>Malcolm Warrand - mwarrand@kmlabs.com<br>+1 303 544 9068 |
| Imra | Imra | Fibre Er<br>Fibre Yb<br>Fibre Tm | Imra, USA - lasers@imra.com<br>+1 734 930 2560 |
| Menlo | Menlo | Fibre Er, Yb | Menlo Systems GmbH, Germany - sales@menlosystems.com<br>+49 89 189166-0 |
| Wavetel | Menhir Photonics | | Arnaud Bout - about@wavetel.fr - +33 (0)6 83 55 19 47 |

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[5] This is true above all for amplified systems.