



fast, powerful and efficient femtocryble

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The FEMTOCRYBLE project is undertaking groundbreaking work researching the Ytterbium compounds for use in lasers. Here, **Dr Frédéric Druon** of the Institut d'Optique discusses the project and why France leads the way in developing ultrashort-pulse lasers

Fast, powerful and efficient



What are 'New Yb-doped crystals and laser architectures for the development of a chain femtosecond laser high power' (FEMTOCRYBLE)'s three major research objectives?

The main objective of FEMTOCRYBLE is to use newly developed Ytterbium (Yb)-doped lasers to improve the performance of diode-pumped femtosecond solid-state lasers in terms of power, pulse duration, energy and efficiency. For this, the first research objective concerns crystal improvement; a second concerns the study of the spectral and thermal properties of the crystals in laser condition; and a third concerns the development of innovative laser architectures and geometries.

How is the project structured?

FEMTOCRYBLE is a straightforward, vertical project. We proceed with growing the crystals, undertaking the laser experiment and then transferring the technology to a company. The strength of the project is based on strong collaboration between partners. Improvements in laser quality influence laser performance, which helps us to understand problems

that might be encountered in future crystal generation.

France is at the forefront of innovation and research in this field; why is this?

There is particularly strong international competition in this field. Nonetheless, French laboratories have been positioned as one of the world leaders on crystal and laser developments for ultrashort-pulse generation based on new Ytterbium (Yb)-doped crystals. This leadership is due to a strong collaboration between French laboratories expert in material science, such as CIMAP and LCMCP, and those (such as LCF) which specialises in diode-pumped femtosecond laser devices. This national focus and leadership has already led to several important breakthroughs using very innovative Yb-doped crystals. In 2006 we developed Yb:CALGO, the shortest pulse ever obtained with an Yb-doped crystal, and undertook the first demonstration of laser operation and femtosecond pulse generation of another very promising crystal, Yb:CaF₂.

Has a multidisciplinary approach proved important to FEMTOCRYBLE?

The multidisciplinary nature of the project has been key to our success. Working together has enabled us to achieve the promotion of Yb:CaF₂ and Yb:CALGO, to the point that it is now recognised worldwide. Today, industrial products and even big international projects are derived from the results of this French consortium.

What is your professional background, and how did you come to develop an interest in this field?

My scientific background dates back to the 1990s when I specialised in electronics and optics. In 1996 I graduated from both the French Engineering School: École Supérieure d'Électricité (SUPELEC) and with a Master's degree from Optique et Photonique of the University Paris

XI. By this point I'd already established a firm interest in femtosecond laser technology, especially as I'd already undertaken two undergraduate internships at the Laboratoire d'Optique Appliquée, and a further one at the Laboratoire Charles Fabry. Both of these laboratories specialise in ultrafast lasers.

After graduating, I undertook my military service as a visiting researcher at the Center for Ultrafast Optical Science (CUOS, Michigan) for almost two years. This scientific journey in Gérard Mourou's group confirmed that I'd made the right choice in pursuing a path focused on researching femtosecond lasers. Back in France, in 1998 I started my PhD on diode pumped pulsed solid-state lasers. Since then, I've held a permanent position at the Laboratoire Charles Fabry.

COLLAB MAP

Four key French collaborators are involved in the project:

Laboratoire Charles Fabry de l'Institut d'Optique (LCF), whose Lasers group has expertise in diode-pumped solid-state laser, high power lasers and femtosecond lasers

Laboratoire de Chimie de la Matière Condensée de Paris (LCMCP), which discovered Yb:CALGO in 2005 and has strong expertise on this crystal

Centre de Recherche sur les ions, les matériaux et la Photonique (CIMAP), which unveiled Yb:CaF₂ in 2003 and has leading expertise

Amplitude Systemes (AS) is one of the international market leaders in the field of femtosecond lasers based on Yb-doped materials



Yb:CALGO in thin-disk configuration.

Crystallising compound change

Ytterbium (Yb) doped crystals are used in femtosecond lasers for industries as broad as metal drilling, glass texturing and eye surgery. Yet, the traditionally-used compounds are not capable of comparatively short pulses at a high repetition rate. To address this need the **FEMTOCRYBLE** consortium, leads the way in the development and use of novel Yb compounds for diode pumped femtosecond solid-state lasers.

WHEN YTTERBIUM (YB) WAS first discovered in the Ytterby mine near Stockholm in 1787, few might have forecast how important his find would be for diode-pumped femtosecond lasers. In fact, it is now acknowledged that only Yb-doped crystals achieve the high repetition rates and high energy necessary for femtosecond lasers. In the past decade, laser development using Yb-doped materials, and especially Yb crystals, has become one of the most active fields in laser research. These lasers have been used in metal drilling, texturing in automotive fields, and medical applications such as eye surgery. Groups in Germany, the US and Japan are all racing to find the next application for Yb-doped femtosecond lasers.

These laboratories predominantly use Yb:YAG and Yb:KYW crystals for their research. Yet limiting the use of these crystals for lasers imposes obstacles, forcing the team to deal with their narrow emission bandwidths. They are capable only of short pulses typically under 100 fs, and are therefore incapable of being amplified in current systems. To address these issues, laboratories in France have been leading the way in the discovery of new crystals and the development of ultrashort-pulse generation. They have already made several important breakthroughs using innovative Yb-doped crystals, and have broke the shortest pulse record several times using these crystals.

INSTITUT D'OPTIQUE

Among those laboratories spearheading in the development of innovative Yb-doped crystals is the Laboratoire Charles Fabry of the Institut

d'Optique (LCF). Coordinated by Dr Frédéric Druon at the LCF together with the Richard Moncorgé at the Centre de Recherche sur les Ions, les Matériaux et la Photonique (CIMAP) and Bruno Viana at the Laboratoire de Chimie de la Matière Condensée de Paris (LCMCP), the team is working on the 'New Yb-doped crystals and laser architectures for the development of a chain femtosecond laser high power' (FEMTOCRYBLE) project. "We aim to build new Yb-doped lasers by first researching ways in which the development of the crystals needed can be improved," Druon explains. The project is also studying the spectral and thermal properties of the crystals in laser condition, and is examining ways to develop innovative laser architectures and geometries.

ULTRASHORT, ULTRA EFFECTIVE

The work of the Institut d'Optique with in the FEMTOCRYBLE project is focused on producing ultrashort-pulse lasers. Ultrashort pulses are measured at femtoseconds (fs), a unit of time equal to 10^{-15} s. To give a sense of the speed of these pulses, the ratio of one fs to one second is about the ratio of five minutes to the age of the Earth. These lasers use direct diode pumping, which allows for greater efficiency and, as such, more average power. The team is able to increase the repetition rates of a given level of energy, which in turn leads to an increase in the speed of the different processes.

Efficient high-power direct-diode-pumping requires Yb-doped materials. Yet, it has traditionally been difficult to find a crystal that meets the necessary criteria of good thermal properties (for high

power), broad emission bandwidth (for short pulse generation) and high gain (for high efficiency).

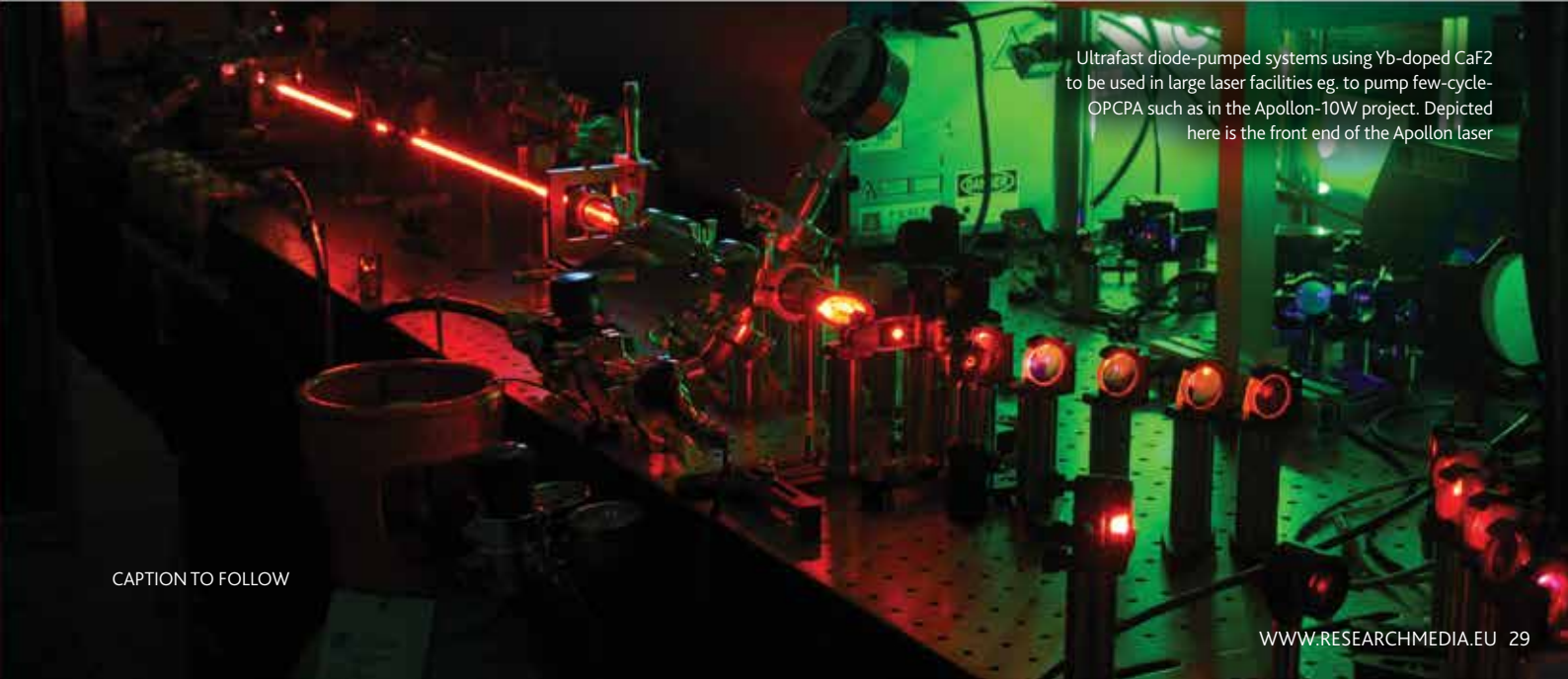
COMPLEMENTARY CHARACTERISTICS

The FEMTOCRYBLE consortium has discovered and developed two compounds, Yb:CaGdAlO₄ (Yb:CALGO) and Yb:CaF₂, to meet these needs. These compounds can handle very high power, whilst also having a very broad emission bandwidth. The two crystals show complementary characteristics and could be used together to reach various operating regimes. For instance, Yb:CALGO leads to shorter pulses than Yb:CaF₂ and seems more accurate for oscillators or high repetition rate amplifiers, whereas Yb:CaF₂ would better work at lower repetition rates within high energy amplifiers due to its long lifetime. In terms of emission wavelength, they are completely compatible ranging from 1020 nm to 1070 nm.

"These compounds are also promising for the building of high power lasers, as they can be directly diode-pumped with diodes emitting around 900-980 nm, the spectral band which corresponds to the absorption of Yb³⁺," Druon observes. The compounds have a very simple structure based on only two manifolds, which avoids any parasitic effects that can heat the crystal.

CRYSTAL CLEAR WORK

To achieve these innovative and ambitious goals, the team has worked on producing extremely high quality crystals. Crystal quality is a key factor in the development high efficient



Ultrafast diode-pumped systems using Yb-doped CaF₂ to be used in large laser facilities eg. to pump few-cycle-OPCPA such as in the Apollon-10W project. Depicted here is the front end of the Apollon laser

INTELLIGENCE

FEMTOCRYBLE

OBJECTIVES

To develop a future generation of high-efficient, high-power and short-pulse lasers based on innovative Yb-doped crystals prosperous for ultrashort pulse production and amplification, namely Yb:CALGO and YbCaF₂. This includes the improvement of the know-how in the crystal growth and the development of innovative laser designs.

KEY COLLABORATORS

CIMAP: Richard Moncorgé, Patrice Camy, Jean-Louis Doualan

LCF: Frédéric Druon, Patrick Georges, Sandrine Ricaud, Alain Pellegrina, Dimitris Papadopoulos, Florence Friebe, Julien Pouysegur

LCMCP: Bruno Viana, Pascal Loiseau, Anaël Jaffres, Akiko Suganuma

AS: Antoine Courjaud, Eric Mottay, Clemens Hönninger, Martin Delaigue, Yoann Zaouter

PARTNERS

Laboratoire Charles Fabry de l'Institut d'Optique (LCF) • Laboratoire de Chimie de la Matière Condensée de Paris (LCMCP) • Centre de Recherche sur les Ions, les Matériaux et la Photonique (CIMAP) • Amplitude Systemes (AS)

FUNDING

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pone.0068965](http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0068965)

FRÉDÉRIC DRUON graduated in 1996 with a joint Supelec and Optics-Photonics Master (Univ. Paris-Sud). He obtained his PhD in 2000 and joined in 2001 the CNRS at the LCF (Laser Group). He received the Prix Fabry de Gramont 2005 and the Prix Jean Jerphagnon 2011 for his research on diode-pumped femtosecond lasers.

lasers, and much work has been done by CIMAP and LCMCP to improve the growing processes of doped CaF₂ and CALGO. Moreover, new growing techniques such as epitaxial growth is explored to produce thin crystals to access to new laser geometries. Crystals are optimally doped to match the laser experiment whilst ensuring high optical quality, and are cut and polished to enable the researchers to access the best crystallographic axes.

In order to validate the quality of the crystals, the team performs several optical characterisations. They use classical techniques, such as roughness and AFM imaging, to give information on both the sub-micron and macroscopic scale. These techniques are combined with novel approaches, such as speckle measurement (to access to the diffusion losses) and wavefront analysis (to access to phase distortion due to inhomogeneities). In situ, laser characterisations including spectral tunability, thermal analysis and femtosecond-pulse generation and amplification are performed to validate the crystal improvements.

HOT AND COLD

Once produced, the team utilises the potential of these crystals through cryogenic and thin-disk technologies. These amplifiers ensure a good beam quality and short and intensive laser pulses, which can further increase the average power of the laser. Thin-disk geometry allows a more efficient heat extraction, whilst raising the limits that a crystal will fracture under thermal stress. Alongside cryogenic cooling this enables the crystals to achieve better thermal properties, and inevitably greater levels of power.

The team is aiming at an average power of 100 W, with pulse durations in the range of 100 fs at energies between 1 mJ to a few tens of mJ. This would improve the peak power achieved so far by one order of magnitude. This progression will constitute the first steps towards the manufacturing of lasers with even higher intensities.

A PULSATING NEED

The Institut d'Optique's work in developing such ultrashort-pulse lasers is undertaken to meet a real-world need, and FEMTOCRYBLE includes a laser French company, Amplitude Systemes (AS), which is one of the international leaders in the femtosecond lasers based on Yb-doped materials market. Lasers already have multiple applications, but by advancing their capabilities, the team is looking towards what might else be achieved. In industry, lasers are used for micromachining and material structuration, both of which require the high level of precision attainable through ultrashort-pulses. This level of precision and accuracy is also needed in the treatment of tissue in eye surgery, for instance.

Furthermore, many laboratories are conducting experiments which demand high energy pulses at higher repetition rate than the ones currently available. There are a number of experiments that require numerous laser shots for statistical reasoning. Free Electron Laser (FEL) experiments need high-energy lasers to generate high repetition rate secondary source. Moreover, such a high-energy laser class can also be used in laser-driven inertial confinement fusion.

IMPACT

The impact of FEMTOCRYBLE is already apparent. Both Yb:CaF₂ and Yb:CALGO laser crystals are already commercially available and numerous international laboratories and companies are also following the move including such crystals in their lasers. As well as showcasing the groundbreaking efforts of French laboratories, the work is also improving the expertise and collaborations throughout the industry.

The importance of these breakthroughs is shown in the calibre of experiments using the FEMTOCRYBLE consortium's research. "All of the improvements made by the FEMTOCRYBLE laboratories concerning crystal growth and laser demonstration highlight the interest in the crystals, and increase their status in the laser community," Druon reflects.



Multipass amplifier using Yb:CaF₂.