Optical to RF Synchronization for Accelerators and Free Electron Lasers

Image: The Dalian Coherent Light Source Facility / DICP

Highly intense light sources such as free-electron lasers (FEL) are the key to cutting-edge research on the molecular level. With ultrashort pulses, they offer the necessary attosecond temporal and subatomic spatial resolution. But their performance depends on the stable synchronization of optical and microwave sources in a multi-kilometer range. So, such high-end light sources often implement optical timing distribution systems that satisfy their stringent synchronization and timing requirements. But one challenge remains for the operation of these facilities: How to incorporate the existing electronic components into the precise optical timing distribution? For this task, the Balanced Optical-to-Microwave Phase Detector (BOMPD) may play a crucial role.

The Situation

For the light generation in a free-electron laser source, multiple electrical and optical components need to be synchronized to a master clock, which is the facility's RF standard. The challenge is that these components are distributed over kilometer-long distances and the application requires a synchronization precision in the few-femtosecond regime. But electrical or uncorrected optical timing solutions can't provide the stability necessary for such accuracy. As a result, these timing solutions are not suitable, and an optical Timing Distribution System (TDS) is needed.

Such a system comprises an optical master oscillator (OMO), i.e., a laser synchronized to the RF standard, and an optical network that distributes its signal to the clients via fiber links. Subsequently, the distributed signal needs to be synchronized to the clients at the output of the fiber links.

Within such a timing distribution system, there are two critical sites with respect to the optical-to-RF synchronization:

1) At the input of the TDS, when the frequency of the master clock is imprinted on the OMO.
2) At the output of the TDS, generate an RF signal based on the OMO signals at an output of a fiber link.

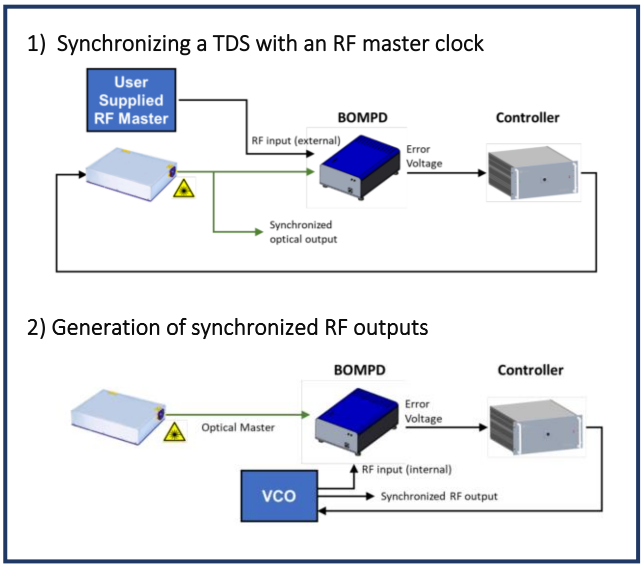


Figure 1 Applications of a BOMPD within a Timing Distribution System of a Free Electron Laser.

In both situations, it is important to efficiently transfer the signals between the optical and electrical regimes with high precision. Otherwise, you will lose much of the benefits you gained by using a TDS.

The Challenge

In general, if you want to synchronize a train of light pulses with an electrical oscillation, you need to convert the two signals to one common format. For this, direct photodetection was the method of choice as it converts photons into a microwave signal. But while an established technique, it also has its limits.
Most critical, the limited resolution of the direct photodetection on the order of few hundred of femtoseconds is not sufficient for the accuracy requirements of advanced accelerator facilities and especially, free-electron lasers. Such high-end light sources require timing accuracies far beyond this. But how can such extreme precision be ensured?

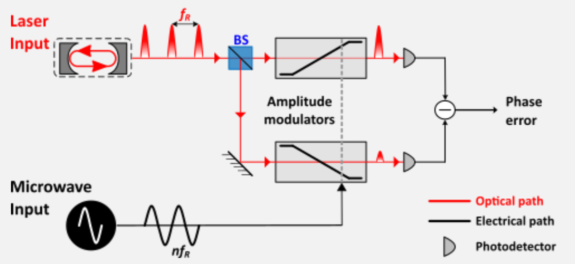
The Solution

The main issue of direct photodetection is the additional phase noise from amplitude fluctuations during detection and its limited timing resolution of approx. 100 fs using traditional microwave mixers. To overcome these, the BOMPD uses a different approach: to synchronize a microwave signal with an optical signal, the BOMPD compares the two signals in the optical and not in the electrical domain. This way, the adverse timing properties of direct photodetection can be disregarded and a timing jitter of 20 fs RMS and below can be achieved for the synchronization.

In a TDS, the BOMPD is therefore used as a synchronization device to precisely sync the master RF-clock with the OMO. It compares the OMO's optical pulses with the facility's RF standard and modulates the frequency of the OMO if necessary. This way you generate an optical timing signal highly synchronized with the RF standard.
At the outputs of the TDS, a voltage-controlled oscillator is connected to the BOMPD. This way the synchronized optical signal at a fiber link output can be used to generate a low noise microwave signal with a multiple of the master laser's repetition rate.

How does a BOMPD work?

Like "direct photodetection", the BOMPD receives two input signals: an optical pulse train and a microwave signal. But instead of detecting the optical signal first and then comparing the phase difference between two microwave signals, the BOMPD does two different things:
First, it translates the microwave signal into an optical amplitude modulation. And second, it detects the modulated signal using a balanced detector. When monitoring the output signal of the balanced photodetector over time, it reveals the phase correlation between the laser input signal and the microwave input signal.



At the Dalian Coherent Light Source (DCLS) in China, for example, the timing experts chose to implement such highest synchronization standards of the TDS at 15 remote locations. Thanks to this innovative technology, the resulting timing jitter for the DCLS is well within the requirements.

Other large accelerator facilities around the world, like FERMI in Trieste, LCLS in Stanford and the Shanghai XFEL in China also rely on this technology, and hopefully, there will be many more in the future. Because with each of these facilities, there is a whole new range of opportunities for innovative experimentation that might help to understand some more secrets of our world.

For more information on the BOMPD as well as other timing and synchronization products, please contact

Cycle

Cycle GmbH

Phone: +49 40 298486-0
Email: contact@cyclelasers.com

www.cyclelasers.com