Romanian Reports in Physics, Vol. 62, No. 3, P. 644–651, 2010

LASER INSTRUMENTATION

Dedicated to the 50th LASER Anniversary (LASERFEST-50)

DESIGN CONSIDERATIONS FOR AN INTERFEROMETER FOR COHERENT COMBINATION OF ULTRASHORT LASER PULSES

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(Received June 10, 2010)

Abstract. Real-time interferometric method and system are proposed for monitoring the thermal, mechanical and optical fluctuations in laser amplification chains. Both the applied methods and the used electronics are specially selected to allow building a real-time, high speed system capable to work in closed loop configuration. The system is developed to supervise and control the piston error in the coherent combination of ultra-short and ultra-intense pulses.

Key words: high-resolution real-time interferometer, coherent combination of ultra-short pulses.

1. INTRODUCTION

While the scientific knowledge evolved from macroscopic to microscopic, more intense and localized fields are required in order to deepen our understanding of the interactions and phenomena in the nature. In order to push the tests of the microscopic world to the limits, large facilities are built and technological development supports the scientific efforts. However, each technology has its range of applicability and, once the limits are reached, new technologies have to emerge.

One well known example in the recent years is related to the development of the processors for the computers. In the last 15 years it was an exponential increase of the processors capability, measured in number of Mega-instructions per second (Mips). For several years, increasing the processing capability was made by increasing the clock speed of the microprocessors. Doing this it was impossible to achieve more than one executed instruction per clock cycle. To overrun this limitation, a new architectural concept was invented: the superscalar microprocessor, which means that the microprocessor has multiple kernels working in parallel. Recently, because the technologies are approaching their limits, the growing ratio of the clock frequency diminished. Again, to counteract this trend, the specialists made an architectural improvement and the result is the multi-core processor technology. Consequently, the emerging technologies which now push the limits of the computational speed are related to the use of parallel core processors.

A similar case is met in development of ultra-intense laser pulses. The increase of the peak power of the laser is made mainly by up-scaling ultra-short pulses laser systems to the highest possible intensities in master oscillator - power amplifier (MOPA) serial architecture. The present technological bottlenecks limit the output of such systems to presumably few PW. In order to reach EW power levels, parallelization of such multi-PW serial MOPA systems was proposed by the Extreme Light Infrastructure project [1].

In this case, parallelization implies new techniques and methods to make coherent combination of the pulses. The coherent combination is implemented since many years in continuous wave laser systems where, in general, the phase shifts of the lasers are controlled. For pulsed laser systems, one has to control not only the phase but also the total optical path from source to the destination, in order to spatially and temporally overlap the ultra-short pulses. As the duration of the optical pulses approach few periods, it is essential to have the same well defined optical path length in all the parallel laser amplifier chains, with a precision of a laser wavelength fraction. This is a difficult task, as the length of such amplification chains reaches hundreds of meters on the one hand, and the pulse duration is tens of femtoseconds, on the other hand. Interferometric methods are suitable for the characterization of the dynamics of the optical path in such amplification chains.

Sources of optical path variations in MOPA systems are actually thermal and mechanical fluctuations. Mechanical fluctuations are limited using monolithic floor buildings and stable mechanical tables and opto-mechanical mounts. In amplifiers with population inversion, the thermal fluctuations are induced in the amplification crystals during the pumping. As an example, for Ti:Sapphire crystals one can evaluate the thermal fluctuations of the optical path in the crystal by computing the variation of the crystal length and of the refractive index.

For 1 cm crystal, the optical path shift is ~80 nm / K; as a consequence, for 16 pass amplifier, the optical path shift is 1,280 nm = ~3 $\lambda/2$ (λ = 800 nm). For coherent pulses combination, the total optical path variation needs to be less than $\lambda/4$ = 200 nm.

To characterize such optical path fluctuations, the solution proposed here is an interferometric one.

2. EXPERIMENTAL SETUP

The proposed experimental setup for monitoring the optical path shift is presented below.

The system includes a He-Ne laser as the light source for the interferometer. In the measuring arm of the interferometer an *Amplifier Crystal* is placed, whose optical path variations are going to be interferometrically measured. The interferometer is followed by dedicated electronics, which process the sine and cosine signals generated by the photo-detecting diodes. The main specifications of the interferometric monitoring setup are (Fig. 1):

– high-speed, real-time, code-counting method interferometer;
– λ/32 (~20nm for λ = 633 nm He-Ne laser) resolution;
– 2 m/s speed for λ/32 resolution;
– simultaneously λ/32, λ/16 monitoring at 2m/s, 4m/s respectively;
– fault tolerant for high speed fluctuation;
– monitoring the phase quadrature of optical interference signals;
– suitable for closed-loop operation.

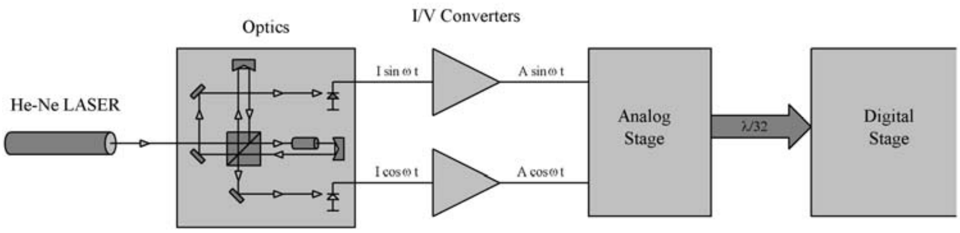

Fig. 1 – Experimental setup for monitoring of optical path shift.

The interferometer, first introduced by Albert Michelson in 1881, has been developed in time as a measurement instrument of high accuracy. If we consider interfering beams of equal intensities, the irradiance of the light in the interference fringes field is:

$$I = 2I_0\left(1+\cos\left(\frac{2\pi}{\lambda}\left(r_m - r_r\right)\right)\right), \tag{1}$$

where I_0 is the irradiance of the two reflected and recombined beams, r_m is the distance to moving mirror, r_r is distance to fixed mirror, and λ is He-Ne laser wavelength. If the moving mirror is displaced with Δx, the optical path length changes with $2n\Delta x$, were n is the refractive index of the medium through which the light travels. The factor 2 is because the light travels twice the distance to the mirrors. In this case, the irradiance becomes:

$$I = 2I_0\left(1+\cos\left(\frac{2\pi}{\lambda}(2n\Delta x)\right)\right). \tag{2}$$

This formula shows that if we know the wavelength λ of the light, we can calculate the displacement of the moving mirror from irradiance variation. At this moment it is important to notice that only the displacement can be measured.

From original Michelson interferometer numerous derived versions were developed over the time, all being able to measure only the displacement (or relative distance), not the absolute distance. If we deal with a single frequency of light beam (monochromatic light), we have a homodyne interferometer; if we have a beam with two frequency components we have a heterodyne interferometer. In our case, we have a homodyne interferometer with two optical outputs of π/2 phase difference. The irradiances of these beams are respectively:

$$I_{S0} = 2I_0\cos\frac{4\pi n\Delta x}{\lambda}; \quad I_{S90} = 2I_0\sin\frac{4\pi n\Delta x}{\lambda}. \tag{3}$$

From the equations (3), we easily obtain:

$$\Delta x = \frac{\lambda}{4\pi n}\operatorname{arctg}\frac{I_{S90}}{I_{S0}}. \tag{4}$$

Two photo-detectors convert the π/2 phase difference optical outputs in corresponding sine and cosine electrical signals. The main advantage of using two signals with a phase shift of π/2 (quadrature signals) is that we can easily sense the direction of movable mirror. If the mirror is moving forward, the cosine signal lies after the sine signal. If the mirror is moving backward, then the cosine signal lies before sine signal.

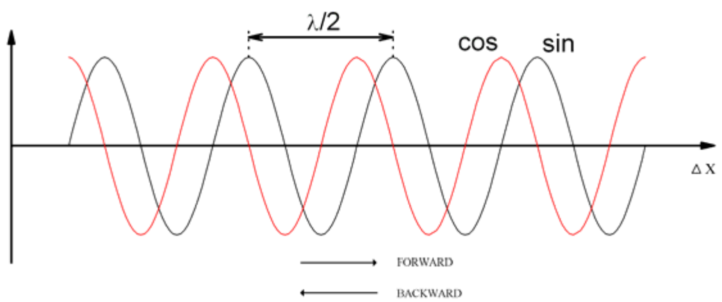

Fig. 2 – Two π/2 phase shifted signals in order to sense the direction of the displacement.

As we can see in Fig. 2, every fringe (a fringe is a full cycle of light intensity variation, going from light to dark and back to light) corresponds to a path difference of a half wavelength of the laser.

2.1. PHOTO PREAMPLIFIER

The two photo-detectors (PIN photo-diodes) act as current sources modulated by the irradiance of the incident light. In order to further process these signals, the current must be converted in voltage, so the next stage consists in two current-to-voltage converters realized with trans-impedance amplifiers, having the transfer characteristics as the ratio:

$$\frac{V_0}{I_{in}} = R_g\,, \tag{5}$$

where V_0 is the output voltage, I_{in} is the input current, and R_g is the trans-impedance of the circuit. A typical trans-impedance circuit is shown in Fig. 3.

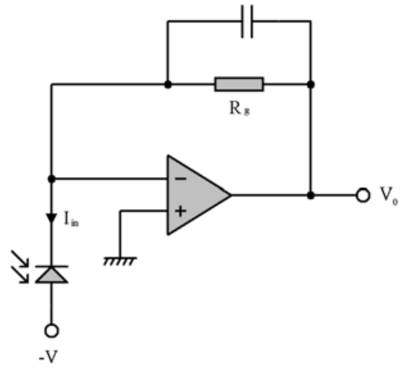

Fig. 3 – The trans-impedance amplifier used as current-to-voltage converter.

To have this circuit compatible with the overall requirements of the system, we have to analyze the following electrical characteristics: trans-impedance, bandwidth and signal-noise ratio. Because it is hard to calculate the beam irradiance losses in optical arms of the interferometer and because PIN photodiodes with different values of responsivity can be used, we can only roughly estimate the necessary trans-impedance in order to have an output voltage of 500mV. Fortunately, the next stage (analog stage) can work in proper condition if the input signal amplitude can vary by a factor of 2. From previous experiments we established that a trans-impedance R_g = 50 kΩ is more than enough for our purpose.

In order to fulfill the spec of a moving mirror speed of 4 m/s as it was specified earlier, we need to calculate the necessary bandwidth of the preamp. The relationship between speed and bandwidth is:

$$V[\text{m/s}] = BW[\text{Hz}]\cdot\frac{\lambda[\text{m}]}{2}\,. \tag{6}$$

For a moving mirror speed V=4 m/s and wavelength λ=632.8 nm for the He-Ne laser, the bandwidth BW is:

$$\mathrm{BW} = \frac{2V}{\lambda} = \frac{2 \cdot 4}{632.8 \cdot 10^{-9}} = 12,642,225.03\,\mathrm{Hz} \cong 12.6\,\mathrm{MHz}. \quad (7)$$

This value means one has to use a wideband photodiode preamplifier, based on a high speed operational amplifier. A suitable operational amplifier for the I/V converter is OPA 656 (*Texas Instruments*). With its large-signal bandwidth of 75 MHz and input current noise of $1.3\mathrm{fA/Hz}^{1/2}$, this circuit is specially designed for wideband and high gain amplifiers. However, the junction capacitance of the photodiode severely restricts the bandwidth. Any voltage signal developed by the diode interacts with junction capacitance, reducing the output current. This restriction can be surpassed through three methods [2]:

- Signal isolation;
- Photodiode bias;
- Photodiode bootstrap;

Another problem arises when using high gain, wideband amplifier: the noise, or signal / noise ratio. A photodiode amplifier, configured as current / voltage converter, is accompanied by a complex noise signal. The main noise sources are feedback resistor (R_g), amplifier's input noise current and noise voltage. Beside the feedback resistor and current noises which appear at the output of the amplifier, the amplifier's input noise voltage is affected by a high frequency gain (named gain peaking noise). This gain results from combination of high feedback resistance and junction capacitance of photodiode, both connected to the amplifier input. And to have the things more complicated, the parasitic capacitance around feedback resistor and $1/f$ intrinsic noise of the operational amplifier itself make the noise behavior of the trans-impedance amplifier to be very complex and hard to analyze. To solve this task in a realistic manner, the noise spectra is split in a series of regions and evaluated separately. However, for a photodiode amplifier with large feedback resistor, the dominant noise is gain peaking noise, and methods to reduce this type of noise have to be applied. Among them, feedback capacitances, low pass filters at the output of the amplifier, use of composite amplifiers, or combination of these methods are mostly used.

Finally, it is useful to notice that, in order to reduce external noise effects, the circuit must be shielded against electrostatic, magnetic and RFI coupling, and the signal should be coupled to next stages through impedance matching coaxial cable.

2.2. ANALOG STAGE

The quadrature signals from the outputs of the photo preamplifiers are converted into two square waves by means of a trigger circuit and then they are accordingly subdivided and counted. The analog stage processing is based on the method of optical fringes code-counting [3], which means a code is associated with every subdivision of the $\pi/2$ phase shifted signals. As a result, real-time high-precision displacement measurements can be achieved with a resolution of $\lambda/16$.

In order to further improve the real-time displacement measurement resolution, we have developed a method [4] to attain measuring increments of λ/32.

Another role of the analog stage is to cancel the low speed noise, or offset drift. The simplest way to do this is to AC couple the signal (a series capacitor at the stage input). The main disadvantage is that the system is unable to work in DC, which is the situation when the movable mirror is steady. This can not be accepted, and another solution shall be developed: a feedback loop (in conjunction with digital stage) which permanently monitors the quadrature signals and applies offset and level signal corrections to them.

The main characteristic of the analog stage is the high speed (the codes are very short pulses of 40 ns width, with rise and fall times of 5 ns). That implies a relatively high complexity design.

2.3. DIGITAL STAGE

At the analog stage output one obtains codes of λ/32 weight each. A sequence of 16 such uniquely defined codes is generated for every fringe period of $T = \lambda/2$. The codes sequencing is different according to the displacement sense in the moving interferometer arm.

The resulting counting codes are numerically processed by the digital stage, which is based on FPGA devices, offering high speed and real time processing. The main role of this stage is to discriminate the associated codes and to accordingly increment / decrement a reversible counter. The counter is able to automatically select the measuring resolution (λ/32, λ/16) according to the displacement velocity, as to agree with the processing speed of the processor. This stage also performs the conversion of counted fractional fringes in metric units and displaying the result.

The system permanently monitors and corrects the quadrature signals (phase shift, amplitude, offset) in limited intervals. When these intervals are exceeded, the system announces the user that the optics must be (re)aligned. Other functions of the digital stage are: data exchange with other devices, processing external commands, data logging, etc.

The analog and digital stages fulfill the so called “hardware counting method” (as opposed to the “software counting method”), which is the most suitable to build a real-time, high speed interferometer.

3. CONCLUSIONS

Piston errors introduced during the pumping of high energy amplifiers in the laser chains are estimated to produce significant distortion and dramatically reduce the intensity of the combined beam resulted from the Coherent Beam Combination (CBC) of ultra intense short pulses. For monitoring the phase and optical path shift, we are developing a high-resolution real-time interferometer. Based on the code counting method, the device is suitable for high speed, real time measurements and is immune to vibrations which might appear in the laser system. The device consists of an analog stage which generates the counting code, later processed by the digital stage. The analog stage ensures 20 nm resolution, 2 m/s optical path variation speed measurements and has low sensitivity to variations of quadrature signals amplitude. The digital stage is based on FPGAs with 10 ns signal processing time. The algorithm provides simultaneously measurements with increased speed for lower resolution (20 nm at 2 m/s, 40 nm at 4 m/s), making the system fault tolerant at high speed fluctuations of the optical path. The device contains also a digital-to-analog converter stage, making the instrument suitable for implementation of closed loop control. This technology could be essential for implementation of coherent combination of ultra-short pulses.

REFERENCES

1. http://www.extreme-light-infrastructure.eu/
2. J. G. Graeme, *Photodiode Amplifiers: Op Amp Solutions*, McGraw-Hill, New York, 1995.
3. B. Chen, J. Luo, D. Li, Applied Optics, **44**, 217–223 (2005).
4. S. Sandel, C. Blanaru, OSIM Patent Pending No. A/00807 (2009).