Acousto-optic method of electronic laser phase control for laser interferometry

V I Teleshevsy1, S V Bushuev1, S G Grishin2
1MSTU «STANKIN», Moscow, Russia
2National Research Center «Kurchatov Institute», Moscow, Russia

Abstract. The paper describes a method of electronic control of laser phase for laser interferometry. The method utilizes acousto-optic interaction and ultrasonic wave diffraction. The article presents an opto-electronical scheme for phase shift control with high resolution in reference and object beam without using high voltage.

Keywords: acousto-optics, interferometry, phase shift.

1. Introduction

Modern level of precision measuring devices and technological equipment development makes high demands to metrology as well as to methods of measuring principles realization.

The scientific and industrial technics utilize highly stable laser sources as length standard and require special devices able to shift phase by fractions of the phase. Phase shift laser interferometers are an example of such systems. Phase shift control is important to control phase shift in the field of microscopy, profilometry, dimensional and angular measurements and other fields of industry and nanometrology. The phase shift control is utilized in Linnik’s interferometer [1, 2, 3], Koesters interferometer [4], Fizeau and Twyman–Green interferometers [5].

Traditionally phase shift is controlled by means of mechanical movement of reference reflector via means of piezo-, magnetic, inductive or other kinds of drive. [1-5]. However, these methods have a number of disadvantages, primarily high voltage required by the actuators [6]. Mechanical actuators are also characterized by nonlinearity, hysteresis and wear. Moreover, the principle of mechanical movement hinders accuracy because of requirements of guides linearity, rigidity and movement uniformity. At present only electromechanical methods can be used in order to control movements with less than nanometer resolution [7].

Performance is also a limiting factor. For piezoelectric actuators, phase shift is realized by electromechanical means, shifting the reference reflector by electrically powered piezoelement. The phase shift control signal is either voltage (for piezoelectric actuators) or current (for magnetostrictive or electro-dynamical actuators), defined by a controller. Thus, the reflector movement control is realized by means of an amplitude change, which has low noise rejection, which is crucial. Moreover, piezo-actuators are far from being perfect because of high dielectric constant. High inertia of reflector’s movement limits applicability of controlled phase shift method for dynamical measurements.

However, there are methods of non-mechanical light phase shift based on light propagation through certain media with electrically controlled properties, i.e. acousto-optic modulators. The modulators utilize interaction of acoustic and light field. A sonic wave propagating through transparent crystal (uniform or non-uniform) creates local shrinkage and expansion zones, causing refractive index changes, this creating a running phase diffraction fringe. A beam of light passing through the crystal...
diffracts, creating a number of diffraction maxima, directed at equal angles into space [8]. According to phase synchronism $+1^{\text{st}}$ and $-1^{\text{st}}$ orders of diffraction will have different light frequency, lower or higher by sonic frequency value [9]. $1^{\text{st}}$ order will also have corresponding phase shift. Thus the modulated signal’s phase in the $1^{\text{st}}$ order can be controlled by means of altering sonic wave phase.

For $0^{\text{th}}$ diffraction order $E(0)=E^\prime \exp[-i(\omega_0 t+\psi_0)]$, where $E^\prime$ - light wave amplitude, $\omega_0=2\pi v_0$, $\psi_0$ – constant phase shift, light’s phase is independent of sonic wave phase. Meanwhile for the $+1^{\text{st}}$ diffraction order:

$$E(+1)=E^\prime \exp[-i(\omega_0 f t+\psi_0+\varphi)],$$

(1)

the phase depends on sonic wave’s phase $U(t)=U_0 \cos(\Omega t+\varphi)$, where $U_0$ – amplitude, $\Omega=2\pi f$ – sonic circular frequency, $\varphi$ – phase shift induced by power generator. Similarly, for the $-1^{\text{st}}$ diffraction order:

$$E(-1)=E^\prime \exp[-i(\omega_0 f t+\psi_0-\varphi)],$$

(2)

The phase $\varphi$ in (1) and (2) is the phase of electric current inducing the sonic wave, controlled by phase shifter (PS) and step control unit (CU). PS is essentially a chain of delay lines $\Delta t_k$, activated by CU. Thus each delay line creates a phase shift between interfering optical waves $E_1$ and $E_2$ (Fig. 1) $\Delta \varphi_k=2\pi f \Delta t_k$, equal to one step of phase shift. The phase difference $\varphi$ between interfering optical waves $E_1$ and $E_2$ can be calculated as:

$$\varphi=k\Delta \varphi_k,$$

(3)

where $k=0, 1, \ldots, n$ – number of activated phase shift steps.

Since sonic frequency equals hundreds Megahertz’s and the speed of sound propagation through the medium (i.e. for paratellurite crystal) is about 700 meters per second, maximal response time is expected to be no more than 10 microseconds, which is at least one order of magnitude less than response time of currently available piezodrives. Thus, the performance of phase shift interferometric measurements increases significantly.

**Figure 1.** Diagram of acousto-optic interaction.

### 2. Basic principles of electronic phase shift control

The paper describes a new wave method of phase shift control for laser interferometer. The method is based on acousto-optic interaction and is based of transferring the phase of electric modulator
induction into the phase of optical wave within diffraction order. The phase shift of modulator’s inducing current is performed by phase shifter based on a microcontroller with controlled delay of the generator’s signal. The number of phase shift steps is not limited, but a number from 120 to 360 steps is currently most convenient. Such number provides phase shift step size of less then 1 nm. High noise rejection compared to amplitude control assures low step value. A phase shift laser interferometer is designed to utilize two modulators simultaneously in order to modulate laser beam from one common source. One of the modulators is inducted by a 40 MHz signal, the other – by the same signal processed by phase shifter. Thus a heterodyned laser beam is created.

Figure 2 describes the method. Initial laser beam 1 is directed by collimator 2 onto beam splitter 3 and reflector 4, forming parallel beams 5 and 6. The beams 5 and 6 are directed onto acousto-optic modulators 7 and 8 respectively. The modulators produce identical diffraction specters. Both beams diffract into 0\textsuperscript{th} and +1\textsuperscript{st} orders. The +1\textsuperscript{st} orders (flat waves $E_1$ and $E_2$) interfere within the interferometer. Both modulators 7 and 8 are induced by generator 9, but the PS 10 controlled by CU 11 is installed between the generator and the modulator 7.

![Figure 2. Diagram of acousto-optical modulators integrated into interferometer.](image)

3. Prototype of phase shift control system

The phase shifter was realized by means of Spartan-6 FPGA XC6SLX16-2CSG324 [10]. Figure 3 represents the diagram of phase shifter.
Figure 3. Phase shifter realized by FPGA SP601.

The PS (Fig. 3) is based on phase frequency auto-adjustment subsystem 13 (PFAS). The generator 9 inputs the signal into PFAS. The dynamic reconfiguration port 14 (DRP) controls parameters of PFAS. The microcontroller (MC) 15 controls PFAS by means of dynamic reconfiguration port controller 16 (DRPC), connected to DRP. The MC inputs commands and outputs completion signals and diagnostic information via universal asynchronous transponder 17 (UAT) and interface transformer 24.

PFAS is an inbuilt FPGA primitive. Figure 6 represents the structure of FPGA and signal frequencies.

Figure 4. Structure of PFAS realized by Spartan-6 FPGA.
The input signal $f_{in}$ at 200 MHz frequency from the generator is fed into PFAS through digital divisor 25 with division ratio 1, forming output signal $f_D$. PFAS consists of standard elements: phase-frequency detector 26 (PFD), charge pump 27 (CP), low-pass filter 28 (LPF), voltage-controlled generator 29 (VCG). VCG output signal frequency $f_{VCG}$ of 800 MHz is defined by divisor 30 with division ratio 4. Frequency multiplier 31 (FM) is depicted by dashed line. In order to form the reference signal $f_{ref}$ for reference modulator induction and phase signal $f_{phase}$ for phase-shifted modulator induction the VCG output signal is fed into counters 32 and 33 respectively with same division ratio O=20. The counters can also set phase delay measured in VCG signal periods (with factor $K = 0...19$). Thus phase shifter’s is roughly defined by counter 33 as $360^\circ/O$. A stabilized delay line 34 (DL) connected to PFAS is used for fine tuning of phase shift. The connection is selected by multiplexor 35 (MUX). 8 links of delay line provide resolution of $\Delta\phi_k = 360^\circ/(O_{\phi_k}K_{\lambda}) = 360^\circ/160 = 2.25$.

Phase-shifter’s characteristics:
- Signal frequency: 40 MHz;
- Phase shift resolution: 2.25$^\circ$;
- Output signal voltage: LVCMOS 2.5V;
- Output resistance: 50 $\Omega$ (min 32 $\Omega$; max 74 $\Omega$).

Figure 5 presents diagram of FM output signal transformation.

The reference signal $f_{ref}$ is formed by output signal $f_{VCG}$ passing through counter 37 with divisional ratio $O_c$. The counter consists of binary counter 38, characterized by counting range $N=O_c=20$, arithmetical comparator 39 (Comp) and output trigger 40 (T). The comparator forms a meander signal, by comparing counter’s output with a half of counting range $N/2$. The output trigger provides a fixed delay between $f_{VCG}$ and $f_{ref}$ signals.

The phase shifting channel feeds the $f_{VCD}$ signal into stabilized delay line 34 consisting of 8 links. The delay value depends significantly on technological errors, voltage and external temperature. Automatic delay adjuster 36 (ADA) is used in order to stabilize the delays. The ADA inputs both $f_{VCD}$ signal and $f_{VCD}$ signal processed by delay lines. Next, ADA alters delay lines power voltage in order to remove phase shift between its input signals. Thus total delay equals exactly a period of $f_{VCD}$ signal.

![Figure 5. Diagram of signal processing by frequency multiplier output.](image-url)
Phase-shift counter 41 inputs signal from any of the delay line’s outputs, selected by 3 bit code S of multiplexor 35 (MUX). Each delay link corresponds to 45° change of \( f_{\text{VCD}} \) phase. The counter 41 consists of binary counter 42, with counting range \( N_{\text{ps}}=2N=20=40 \), two arithmetic comparators 43 and 44, adder 45, logical adder 46 (&) and output trigger 47 (T). Two comparators are used for forming a 40 MHz meander \( f_{\text{ps}} \) as well as phase shifting the \( f_{\text{ps}} \) signal by periods of \( f_{\text{VCD}} \) relative to \( f_{\text{ref}} \) signal. Doubled counting range is required because active phase of \( f_{\text{ps}} \) signal can be left the period of \( f_{\text{ref}} \) signal (while \( K + \frac{N}{2} > N \)). The binary number \( K \) requires 5 bits to code \( K_{\text{max}}=B-1=19 \).

The commercially available components are sufficient to realize the presented control method.

The phase shift resolution is \( \Delta \phi_s=360^\circ/160 = 2.25^\circ \); for He-Ne laser (632.8 nm wavelength) it equals 1.97 nm phase shift resolution, for a molecular fluorine laser it equals 0.46 nm phase shift resolution. If a 256-bit phase shifter is used instead of 160-bit, resolution would be \( \Delta \phi_s=1.4^\circ \), for a molecular fluorine laser it equals 0.3 nm. This significantly increases resolution and accuracy of 3d-reconstruction of measured object’s surface, with phase shift controlled by noise rejecting digital signals instead of a hundred-volt electric voltage.

An experimental setup was built using Renishaw XL-80 (632.8 nm) interferometer. The experiments had proven the method’s efficiency. The results were patented [11, 12].

4. Conclusions

The experiments had proven the possibility of excluding mechanical movements from the phase shift control system in interference systems. Replacing mechanical elements with electronic ones made it possible to lower the cost of the entire system and increase of accuracy and reliability of interferometric measurements due to higher noise immunity in phase modulation rather than amplitude modulation of the control signal with using commonly available electronic components. The resulting measuring system can receive the necessary energy from low voltage and low-power supply systems to increases the compactness and autonomy of the device and reduces the requirements for power electronics of the control system. The experimental data for four phase shifts can be used for a larger number of discrete steps of the phase shift (up to several hundred steps of the phase shift). This will further increase the resolution and stability of data acquisition from interferometric measurement systems. Improving performance also will allow to collect and process phase images in real time for dynamic measurements through the use of more advanced electronic components and photodetectors instead of mechanical components.

5. References

[1] Vasylev V, Gurov I 1998 Computewr signal processing – interferometric application (SPb.: BHH-Saint-Petersburg), pp 153–167
[2] Ignat’ev P & Kol’ner L & Indukaev K & Teleshnevskii V (2015). Laser Modulation Interference Microscopy as a Means of Controlling the Form and Roughness of Optical Surfaces. Measurement Techniques. 58. 10.1007/s11018-015-0792-1.
[3] Grigoriev S N, Teleshovsky V I, Andreev A G, Ignatyev P S, Indukaev K V, Kolner L S, Osipov P A 2015 The metrological certification of laser microscopes based on modulation interferometry principles with controlled phase shift. Vestnik of MSTU «STANKIN», №3(34), pp 67–75
[4] Michalecki G 2001 Automatic Calibration of Gage blocks Measured by Optical Interferometry. Measurement Science Review, Vol. 1, №1, p 93–96
[5] P. de Groot, Jim Biegen et.al. 2002 Optical Interferometry for measurement of the geometric dimensions of industrial parts. Applied Optics, vol. 41, №19, p 3853–3860
[6] http://www.physikinstrumente.com/products.html
[7] Vshnyakov G N, Levin G G, Latushko M I Interference microscopy method. Patent RU2536764, Russian Federation.
[8] Magdich L N, Molchanov V Ya 1978 Acousto-optic devices and application. Soviet Radio, Moscow, 111 p
[9] Kogelnik H 1969 Coupled wave theory for thick hologram gratings. *Bell System Technical Journal*, p 2909–2949

[10] http://www.xilinx.com/support/documentation/data_sheets/ds160.pdf

[11] https://www1.fips.ru/registers-doc-view/fips_servlet?DB=RUPAT&rn=2436&DocNumber=2640963&TypeFile=html

[12] https://www1.fips.ru/registers-doc-view/fips_servlet?DB=RUPAT&rn=9434&DocNumber=2645005&TypeFile=html