Armenian Journal of Physics, 2017, vol. 10, issue 3, pp.99-103

Laser Profilometer with Micron Spatial Resolution

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Received 06 September 2017

Abstract. A new method of remote measurement of the roughness of a surface based on a non-linear optical profilometer is suggested and investigated. It is shown that for the spectral resolution of the spectrograph of 0.2 μm the linear resolution is 18 microns.

Keywords: laser profilometer, surface scan, linear resolution.

1. Introduction

Currently the one of the actual problems is the remote (non-contact) measurement of the relief of a surface, detail configurations, mutual disposition of construction blocks, done on the distance of the tens and if necessary on hundreds of meters providing at the same time the micrometer resolution. The creation of methods and means of measurements, ensuring the solution of the mentioned problems is linked to the implementation of the femtosecond lasers generating the sequence of pulses with temporary jitter per femtosecond unit. With their help is solved the measurement tasks with micrometer precision in the areas of laser profilometry and rangemetry [1, 2, 3]. However, such measurements require the expensive device and additional complicated work for calibration of the means themselves.

In the present work is suggested a new method of remote determination of a surface roughness with the help of non-linear optical profilometer by utilizing a picosecond laser.

2. The Description of Non-linear Laser Profilometer

Dependence of the profile depth of the scanned surface on the carrier frequency of the radiation on the output of the profilometer is given. The block diagram of the optical profilometer using a frequency-modulated (FM) laser pulse designed to measure the surface roughness profile with a micrometer resolution is shown in Fig. 1. The picoseconds pulse of the Gaussian shape from the laser output (PL) is directed to the input of the former of the broadened FM laser pulse, used in further as a probing pulse.

As a source of highly stable periodic sequences may be used picoseconds pulses, in particular we can use a bismuth fiber picosecond laser with a wavelength of 1.3 microns and synchronization of modes on a nonlinear annular mirror with an locked loop system of the repetition frequency, generates pulses with durations of 11.3 ps and energies of 1.65 nJ and repetition frequency f_{rp}= 3.6 MHz. After compression in the compressor on diffraction gratings, the pulse duration can be reduced up to 1 ps, and the use of a fiber amplifier will increase the energy in the pulse up to 8.3 nJ [1].

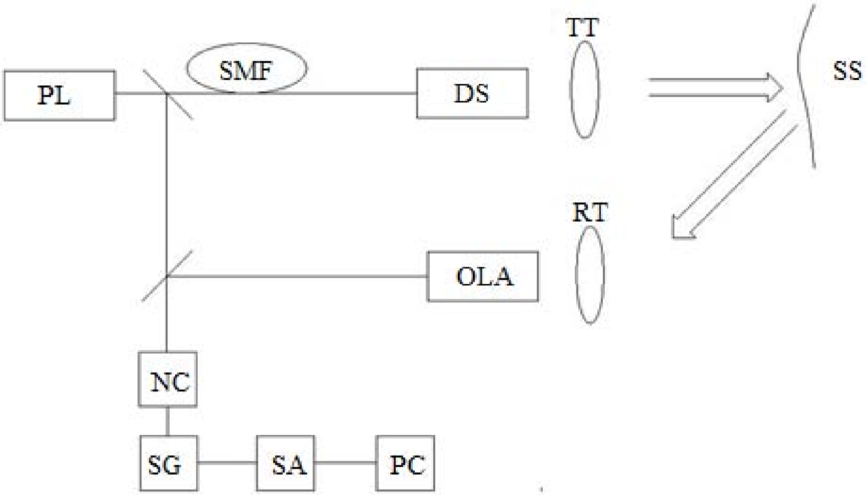

Fig.1. The flowchart of non-linear-optical profilometer: PL-picoseconds laser, SMF - single mode fiber, NC - non-linear crystal, DS-disperser-shaper, TT - Transmitting telescope, SS-scanned surfaces, RT - receiving telescope, OLA - optical linear amplifier, NC - non-linear crystal, SG - spectrograph, SA - spectral analyzer, PC - personal computer.

The former consists of a single-mode fiber segment in which the frequency modulation due to the effect of the self-action and disperser-shaper, which is in the form of a fiber-optic delay line with a controlled dispersion characteristic. In the mode of non-dispersion propagation of the impulse in the fiber, when the impulse duration remains practically unchanged, the law of the change of the output pulse frequency with time is proportional to the derivative of the intensity of the input impulse with time [2]. From the output of the segment of the single-mode fiber FM impulse with a positive chirp is directed to the input of the disperser with a positive dispersion of the group velocity consisting of a pair of diffraction gratings (DG) and a telescope located between them (Fig. 2).

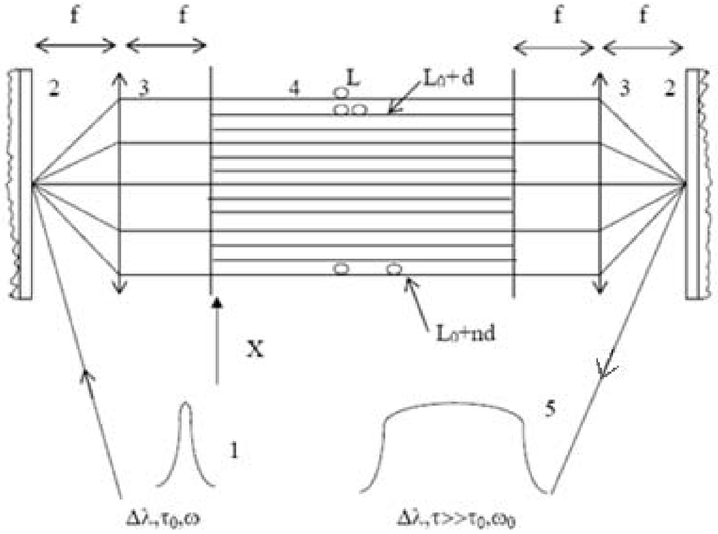

Fig.2. Optical scheme of dispenser shaper with controllable dispersions characteristics. 1 - Initial reference laser impulse, 2 - diffraction grating, 3 - lenses, 4 - the set of single mode optical fibers of various length ($L = L_0 + nd, n \in N, N$ –fiber number), 5 - widened in time output FM impulse.

The input DG is located in the focal plane of the front lens of the telescope and output DG is located in the back focal plane of the output lens of the telescope [3]. From the exit of the front lens of the disperser, the spatial-spectral impulse is directed to the input of the set of single mode optical fiber, which represents the disperser only with the difference that a single-mode optical fiber system is located between the lenses in the focal plane of the lenses [4], allowing to carry out delay control of the spectral components of the impulse, decomposed by the input DG into the angular spectrum. The hardware function and the operating principle of the fiber-optic former-broadener are described in detail in our previous work [4]. Using this former can significantly increase the coefficient of expansion of the FM impulse as compared with the disperser. FM expanded probing pulse

$$E_{pump}\left(r,t\right)=e_1\cdot A_{pump}\left(r,t\right)\cdot\exp\left(j\cdot\left[\omega_0 t+\beta\cdot t^2\right]\right) \tag{1}$$

With the help of the transmitting telescope directed to the investigated object being scanned, located at some distance D_0. In particular, the distance D_0 can be chosen in accordance with the expression of $c/f_{rp}\approx$ 83 m, which corresponds to the overlap of FM pulse with time broadened in the nonlinear crystal formed from the (n-2) th pulse of picoseconds laser with the n-th pulse of the same laser.

In expression (1), $A_{pump}\ (r,\ t)$ - is the amplitude of the probing FM pulse, e_1 - is the unit vector of the polarization of the pulse field, β - is the rate of change of the frequency of the probe pulse, which is determined by the power of the initial picoseconds pulse P_0, diameter A_{eff} and the extension z of the single-mode fiber, in which the self-action of the pulse occurs in the non-dispersion regime, ω_0 – is the bearing frequency, and c is the speed of light in vacuum.

In the regime of the non-dispersion propagation of the pulse in the fiber, when the pulse duration is practically unchanged, the amplitude of the probe pulse can be represented as

$$A_{pump}\left(r,t\right)=\exp\left(-r^2/a^2\right)\exp\left(-t^2/\tau^2\right), \tag{2}$$

where a - is the radius of the beam, $\tau = m\cdot\tau_0$ - is the duration of the probing pulse, τ_0 - is the duration of the initial picoseconds laser's impulse and m – is the coefficient of time expansion of the duration of a picoseconds laser. FM laser pulse reflected from the scanned surface is focused with the help the receiving telescope on the linear optical amplifier.

$$\begin{gathered}E_{pump}\left(r,t-\tau_{pump}\right)=A_{pump}\left(r,t-\tau_{pump}\right)\times\\ \exp\left(j\cdot\left[\omega_0\left(t-\tau_{pump}\right)+\beta\cdot\left(t-\tau_{pump}\right)^2\right]\right),\end{gathered} \tag{3}$$

where $\tau_{pump} = 2(D_0 + \Delta D)/c$, D_0 – is the distance to rough surface, ΔD – is the measured value of the profile depth of the scanned rough surface. After amplification, the reflected pulse (3) is directed to a nonlinear crystal (NC). At the same NC collinear with the reflected also directed a picoseconds reference short pulse of a Gaussian shape from the laser output

$$A_0\left(r,t\right)=exp\left(-r^2/a_0^2\right)exp\left(-t^2/\tau_0^2\right). \tag{4}$$

In the NC a non-linear interaction of the pulses takes place, leading to the generation of a pulse on the total frequency. The complex amplitude of the wave on the total frequency on the crystal output in approximation of the given field can be expressed in the form [2]

$$\begin{gathered}E_K\left(r,t,\tau_{pump}\right)\cong exp\left(-r^2\left(1/a_0^2+1/a^2\right)\right)exp\left(-t^2/\tau_0^2\right)exp\left(-\left(t-\tau_{pump}\right)^2/\tau^2\right)\times\\ exp\left(j\omega_0 t\right)exp\left(j\omega_0\left(t-\tau_{pump}\right)+j\beta\left(t-\tau_{pump}\right)^2\right)\end{gathered}. \tag{5}$$

As it is seen from (5), the amplitude of the wave on the total frequency depends on the time delay between the interacting impulses. Taking into account that the FM duration of probing impulse is manifold greater than the duration of the initial picoseconds pulse (m>> 1), it can be said that for each delay value τ_{pump} corresponds such spatial-time overlap of the pulses in the non-linear crystal, for which the radiation of the picoseconds pulse on frequency ω_0 interacts with the time duration of the FM impulse radiation on frequency $\omega_0 + 2\beta\cdot(t - \tau_{pump})$, where the start of the time segment t corresponds to the moment of the shot of the probing impulse. For the synchronization of the process of radiation registration on total frequency, it is obvious that the frequency of the consecution of the initial picosecond pulses must be equal to $c/2D_0$. The spectral density of the radiation on total frequency (5) can be expressed in the form

$$P_K\left(r,\omega,\tau_{pump}\right)=\left|\int_{-\infty}^{\infty}E_K\left(r,t,\tau_{pump}\right)\exp(-j\omega t)dt\right|^2. \qquad (6)$$

According to the mentioned above and as seen in (6), the value of the maximum of central wave length of radiation on total frequency on the output of the crystal is a function of time delay $2\Delta D/c$ between pulses, i.e. of the depth of the profile of the scanned roughness of the surface. Thus, by sequential point scanning of the rough surface located in a certain distance from the observation place and registering the radiation spectrum on the NC output with spectrometer located on the output of the NC, it is possible clear restore the profile of surface roughness.

3. The Results of numerical simulation

The flowchart of the proposed non-linear optical profilometer of roughness is presented in Fig. 2. Let a picoseconds laser pulse of duration 1ps on the wavelength $\lambda_0 = 1.3\mu$m and of power 10^3 W (energy with 1 nJ) enters into a single mode fiber of length 0.86 m, cross section 50 μm^2 and with non-linearity $n_2 = 3\cdot10^{-20}$ m^2/W, where n_2 – is the non-linear additive to the refractive index, conditioned by cubic non-linearity of the fiber core. The duration of pulse on the output of the fiber remains unchanged and the value of the velocity of change of frequency β of the output pulse becomes equal to $3.5\cdot10^{-24}$ 1/s^2. Then a FM impulse from the output of fiber is directed to the disperser-shaper on which the output time profile becomes supper Gaussian. Principle of operation and basic characteristics of disperser-shaper we described in rather details in work [4]. The parameters of the disperser are selected so that the duration of the widened FM Gaussian pulse on the output becomes equal to 40ps (m=40).

In Fig. 3, the two-dimensional dependence of the radiation spectral density on total frequency upon the frequency and the profile depth of the scanned surface ΔD is shown. As it is seen from figure, to zero value of ΔD corresponds frequency $2\cdot f_0$ = 461.538461 THz ($f_0 = c/\lambda_0$) and to the change of ΔD from -6mm to +6mm corresponds the frequency change from 440 THz to 485 THz (i.e. wavelength from 681.818nm to 628.557nm).

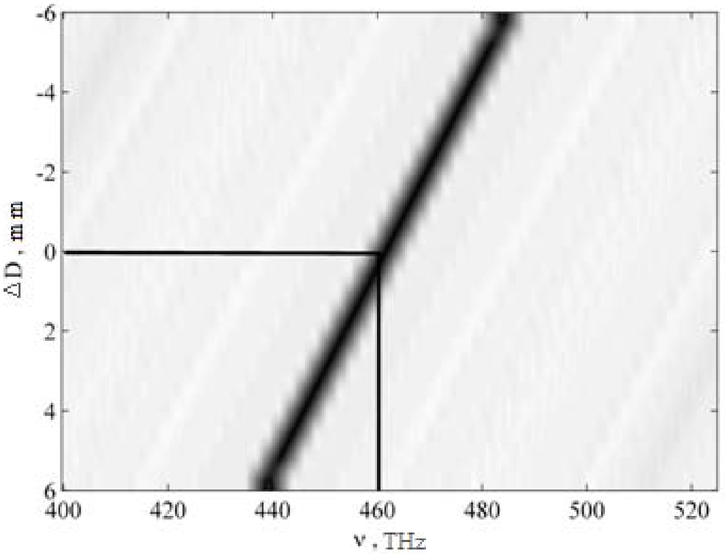

Fig. 3. The two-dimensional dependence of the spectral density of radiation on the total frequency upon frequency and on the depth of the profile of the scanned surface *ΔD*.

The resolution of the mentioned method is determined by the resolution of the spectrograph and, in particularly, for the spectrograph resolution of 0.2 nm it can be reached the spatial resolution of the measurement to 18 μm. As it seen from the mentioned above, the choice of the parameter $\beta \cdot \tau_{pump}$ is determined by the spectral resolution of the spectrograph. In addition, the distance D_0 is determined by the pulse repetition rate of picoseconds laser.

According to numerical estimates, when using a laser pulse with duration of 1ps at a wavelength of 1.3 microns and a power of 10^3 W to ensure the necessary signal/noise ratio, the distance D_0 should not exceed 100 m.

Conclusion

Thus, it has been suggested the realization of a new method of remote measurement of the surface roughness based on a non-linear profilometer. The results of the numerical simulation of the proposed profilometer are submitted. It has been shown that in the case of the collinear generation of the radiation on the total frequency by broadened in time probing pulse of frequency modulated (FM) and spectrally pure reference short laser pulse, an unambiguous correspondence between the carrier frequency of the radiation at the total frequency and the delay between interacting pulses exists. It is submitted the dependence of the profile depth of the scanned surface upon the carrier frequency of the radiation on the output of the profilometer. According to the numerical calculations, the linear resolution of the profilometer at a distance of 100 m is 18 microns.

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