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Femtosecond lasers for astrophysics

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Contents

Abstract. Passively mode-locked continuous-wave (cw) lasers offer the unique feature of generating a strictly periodic train of absolutely identical femtosecond pulses, their emission spectrum representing a comb of equidistant narrow spectral lines separated by an interval determined by the pulse repetition rate. Thus, a cw femtosecond laser is a source of a regular optical frequency comb (OFC), which can be compared to a cesium frequency standard (standard of second) for the precise measurement of optical frequencies for the development of extremely precise atomic clocks, precise spectroscopy, and metrology. One of the main applications of OFCs based on cw femtosecond lasers is precise spectrometric measurements of Doppler shifts in stellar spectra appearing due to the radial motion of stars with respect to the observer. To provide the high measurement accuracy required for the search for and study of exoplanets, a high-precision calibrator for an astronomical spectrometer is required. Such a calibrator can be based on a femtosecond laser OFC. Laser systems for astronomic investigations, including femtosecond lasers for space studies, are considered. It is assumed that the development of these methods will provide direct measurements of the accelerated expansion of the Universe.

Keywords: laser frequency combs, femtosecond fiber laser, cosmic laser, astronomic instruments

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1. Introduction

The advent of a new light source — the laser — and extensive studies of lasers gave impetus to the development of new scientific directions such as nonlinear optics and fiber optics. In turn, advancements in these sciences resulted in the creation of a new type of lasers, in particular, continuous-wave (cw) passively mode-locked lasers. These lasers generate a strictly continuous train of femtosecond pulses. The unique feature of such lasers is their spectrum, consisting of a comb of extremely narrow equidistant lines separated by a frequency interval equal to the pulse repetition rate (f_{rep}). The total width of the spectrum corresponds to the femtosecond pulse duration according to the Fourier transform and can be quite large (up to 1000 cm^{-1}) (Fig. 1). The frequencies of these spectral lines can be measured with a high precision by comparing them with the radio frequency standard (the Cs primary standard for time). Thus, the cw femtosecond laser has two important advantages as a light source: on the one hand, it emits ultrashort pulses (a few femtoseconds in duration) and, on the other hand, its output spectrum consists of extremely narrow lines (a few tens of MHz in width). These unique features have initiated numerous investigations resulting in many important applications (see, for example, Refs [1–8] and references cited therein).

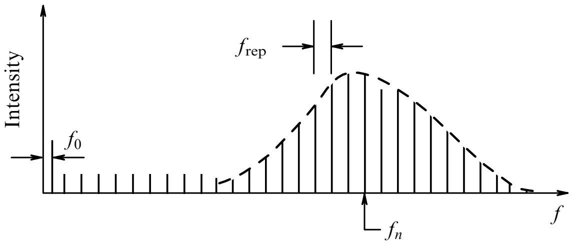

Figure 1. Emission spectrum of a cw femtosecond laser (for clearness, a small number of lines are shown; in reality, their number can reach 10^6).

Precision measurements of optical frequencies are fundamental for investigations aimed at the development of optical clocks. Because the optical frequency comb (OFC) based on a femtosecond laser provides a synthesis of the optical frequency exactly locked to the cesium standard of the second, the appearance of such a possibility became a real breakthrough in the development of optical clocks. The possibility of using cw ultrashort-pulse lasers in the problem of ultraprecise optical clocks was first pointed out by Baklanov and Chebotaev [9]. The rapid development of femtosecond lasers has led to remarkable findings, in particular, the Nobel Prize in Physics 2005 was awarded to Hall [10] and Hänsch [11] for investigations in this field.

Various applications require OFCs with different characteristics, such as the spectral range and spacing between spectral lines. The principle of passive mode locking is universal and can be realized in different laser materials and different laser systems. As a result, many types of femtosecond lasers have been developed. In this paper, we consider laser systems that can be used in optical astronomy and space research. The paper outline is as follows.

In Section 2, the principles and features of the OFC present in the output of a cw femtosecond laser are discussed. Methods for controling OFC parameters and precise measurements of the individual line frequency are considered. Of special importance is the mode spacing in the OFC. Studies in the optical range require the separation of individual OFC modes by available spectroscopic methods. However, the mode spacing is determined by the laser cavity length, and to increase this spacing, it is necessary to diminish the cavity, which presents certain problems.

In Section 3, different types of femtosecond lasers — solid-state, semiconductor, and fiber — are examined.

In Section 4, the features of high-precision astronomical spectroscopy and possible applications of laser methods are considered. The problem of exoplanet searches and investigations is highlighted. The method of exoplanet searches and investigations involves star radial velocity measurements. The high-precision calibration of an astronomical spectrograph is very important in this method. The use of a laser OFC admits solving this problem.

In Section 5, the results of particular developments of precise calibrators for astronomical spectrographs based on laser OFCs are discussed and their application for exoplanet searches is demonstrated.

In Section 6, the main options for increasing the accuracy of spectral measurements to the level allowing direct measurements of the acceleration of Universe expansion are considered.

In Section 7, the newest results of the operation of the femtosecond fiber laser launched into space are discussed and the possibility of operating a satellite-borne laser OFC is demonstrated.

In Section 8, the results of astrophysical studies using the latest femtosecond lasers are generalized and the outlook for such studies is substantiated.

2. Laser optical frequency comb

One of the most important parameters of a cw femtosecond laser is its pulse repetition rate f_{rep}, which affects the pulse energy and, hence, the laser radiation intensity, and also the OFC frequency mode intensity. The higher f_{rep}, the lower the pulse energy, but the higher the individual OFC intensity. Therefore, in applications requiring intense femtosecond pulses, long-cavity lasers with relatively low pulse repetition rates are preferable. On the contrary, for OFC spectroscopy, short-cavity lasers producing frequency combs with relatively large mode spacings are preferable. However, the reduction in the femtosecond laser size presents a considerable challenge. Apart from technological problems arising in reducing the laser size, it is necessary to take into account the dependence of the output parameters of the laser on the pulse repetition rate. Passive mode locking is achieved with the help of a nonlinear bleaching absorber in which the absorption of light begins to saturate at high enough radiation intensities. Because of this, ultrashort pulse lasers have two thresholds: the usual lasing threshold, and the mode-locking threshold. As the pulse repetition rate increases, the pulse intensity proportionally decreases and, therefore, the generation of ultrashort pulses may be entirely impossible at high repetition rates f_{rep} for the given pump density. However, the increase in the pump power presents considerable technological problems.

The frequency modes f_n of the OFC (Fig. 1) are described by the expression

$$f_n = n f_{\mathrm{rep}} + f_0\,, \tag{1}$$

where f_{rep} is the repetition rate of the mode-locked laser, n is the integer mode index running up to 10^6, and f_0 is the comb offset frequency with respect to the zero frequency. The frequency f_0 is determined by the difference between the phase velocity at the maximum of the spectrum and the group velocity of the pulse in the active medium of the laser, i.e., by the intracavity group velocity dispersion (GVD). The optical mode frequency f_n of the comb can be determined from the known values of n, f_{rep}, and f_0. It is remarkable that both frequencies f_{rep} and f_0 lie in the radio range and can be precisely and continuously changed and compared with the Cs standard frequency. Thus, it becomes possible to measure the optical frequency directly and very precisely.

To determine n, it is sufficient to measure the wavelength corresponding to the mode frequency f_n with an accuracy better than the mode spacing of the comb. This can be done by standard spectroscopic methods. Given the known wavelength and the speed of light, we can accurately determine the frequency close to the frequency f_n. Dividing this frequency by the mode spacing of the comb, we obtain n. The repetition rate f_{rep} can be continuously tuned by changing the laser cavity length with a piezoelectric controller and measured with a fast photodiode and oscilloscope or a radio frequency spectrum analyzer.

The control and measurement of the offset frequency f_0, which is a part of f_{rep} (Fig. 1), is more complicated. Because f_0 depends on the dispersion of the active medium in the cavity, it can be tuned by changing the intracavity GVD, the required change being rather small and strictly controlled. The GVD of the active medium depends on the population inversion, which in turn depends on the pump laser power. Thus, the offset frequency f_0 can be controlled by small variations in the pump power. The value of f_0 can be precisely measured by the interferometric method of comparing the frequencies of the low- and high-frequency ends of the comb [12]. To do this, the total width of the comb spectrum should exceed one octave, i.e., the doubled frequency of the low-frequency end of the comb should be smaller than the frequency of the high-frequency end of the comb. As a rule, the width of a

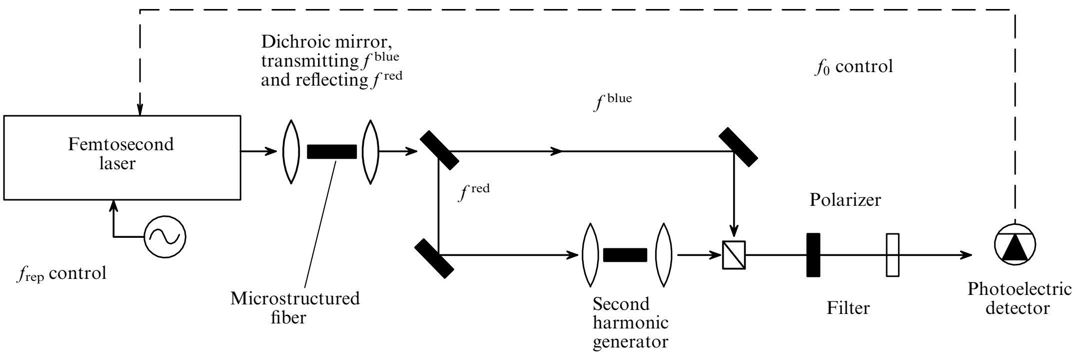

Figure 2. Schematic for measuring the frequency f_0.

frequency comb from a femtosecond laser is close to the gain bandwidth of the active medium, which is considerably narrower than the required width. Because of this, to obtain an octave spanning frequency comb, the special nonlinear effect of supercontinuum generation [13] in strongly nonlinear media, such as microstructured optical fibers like photonic crystals, is involved [14, 15]. Supercontinuum radiation is directed into the so-called $f-2f$ interferometer (Fig. 2) where the second harmonic of a group of modes from the low-frequency end of the comb is generated in one of the interferometer arms. Due to interference between radiation from the high-frequency end (f^{blue}) of the comb and frequency-doubled radiation ($2f^{\text{red}}$) from the low-frequency end of the comb, beats appeared at the beat frequency f^{beat} detected with a radio-frequency spectrum analyzer. By using formula (1) for interfering frequencies, we obtain the frequency f^{beat}:

$$f^{\text{beat}} = 2f^{\text{red}} - f^{\text{blue}} = 2(nf_{\text{rep}}+f_0) - (2nf_{\text{rep}}+f_0) = f_0\,. \quad (2)$$

Thus, we see that this procedure gives the required frequency f_0.

Precise optical frequency measurements with the help of laser frequency combs were applied to determine the frequencies of secondary optical frequency standards (the narrow spectral lines of methane, acetylene, and iodine). These lines were used to create lasers emitting a very narrow (reference) line at frequency f_{ref}. If the frequency f_{ref} falls in the comb spectrum, it can be utilized to stabilize the comb, thereby eliminating the necessity of using an $f-2f$ interferometer.

Thus, the OFC generator built around a cw femtosecond laser is a synthesizer of precise optical frequencies. For optical spectroscopy, it is important to increase the mode spacing in the comb. If the mode spacing exceeds a few GHz, it is possible to exploit standard spectral instruments resolving these modes. The mode spacing in the comb can be increased by decreasing the cavity length in femtosecond lasers of different types.

3. Types of femtosecond lasers generating optical frequency combs

The effect of passive mode-locking is universal and can be realized in various types of lasers.

3.1 Solid-state lasers

The authors of paper [16] managed to diminish the size of a classical femtosecond Ti:Sapphire laser based on the Kerr lens effect. They used a ring cavity with one of the mirrors covered with a so-called chirped coating to control the GVD for shortening the pulse duration. The size of this unique laser is so small that it can be placed on a 2-euro cent coin (or a 50-kopeck piece) [17]. The pulse repetition rate is 10 GHz, providing the resolution of comb modes with a spectrometer after supercontinuum generation. However, such a high repetition rate was achieved using an expensive and rather large 10-W cw Verdi (Coherent) pump laser. This complicates the laser setup. The disadvantage of this system is in fact the impossibility of pulse amplification, which prevents its applications in astrophysical studies.

Apart from sapphire, solid-state femtosecond lasers also employ some ceramic materials. Thus, a miniature solid-state Kerr-lens mode-locked laser emitting femtosecond pulses with a pulse repetition rate of 15 GHz was described in recent paper [18]. The scheme of this laser is shown in Fig. 3. The replacement of a sapphire crystal by ytterbium-doped laser ceramics provides significant advantages. Instead of the complicated and expensive 10-W pump system, a 1.1-W laser diode with an optical fiber is involved. The smaller difference between the pump wavelength (976 nm) and the output wavelength (≈ 1080 nm) of the laser than in sapphire provides lower thermal losses, while the thermal conductivity of ceramics is higher than that of sapphire. This alleviates the problem of cooling. Finally, because the laser wavelength coincides with that of an Yb:fiber, an efficient fiber amplifier can be tapped. The authors of Ref. [18] point out that the laser size can, in principle, be further diminished and the repetition rate increased to 30 GHz. The main challenge is the fabrication of highly reflective optical mirrors with the radius of curvature smaller than 5 mm.

3.2 Semiconductor lasers

Continuous wave femtosecond lasers are pumped, as a rule, by semiconductor injection lasers (laser diodes). Along with

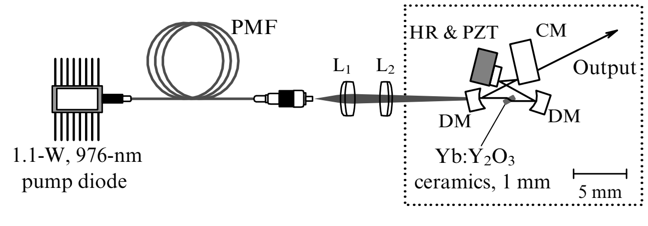

Figure 3. Solid-state femtosecond laser with a pulse repetition rate of 15 GHz [18]. PMF: polarization maintaining fiber; L_1 and L_2: achromatic lenses; HR&PZT: high-reflection mirror on a piezoelectric translator; CM: output mirror; DM: dichroic mirror.

remarkable operation parameters, such as their compactness, high efficiency, comparatively low cost, and a spectrum close to the absorption bands of the active medium of femtosecond lasers, an important feature of semiconductor injection lasers is their precise continuous tunability, required for OFC stabilization.

Semiconductor materials are also successfully used as saturable absorbers providing passive mode-locking. The case in point is a special multilayer SESAM (semiconductor saturable absorber mirror) structure [19] and similar systems considerably reducing the lasing threshold of femtosecond lasers, which is favorable for decreasing the laser size. Semiconductor structures can also be utilized as active media optically pumped by laser diodes. All this facilitates the development of compact and efficient lasers.

The authors of Ref. [20] described a disc laser in which semiconductor materials served as the active medium and saturable absorber. The design of this laser provided a reduction in the laser cavity along with increasing a pulse repetition rate up to 50 GHz. However, it is necessary to solve the problem of increasing the output power required for nonlinear transformations to obtain the desirable spectral characteristics of OFCs.

3.3 Fiber lasers

The development of fiber optics resulted in the creation of fiber lasers based on single-mode fibers with a core doped with rare-earth ions. These lasers have a number of unique properties. Because light in them propagates in a waveguide, the necessity for a rigid and precise arrangement of laser elements is eliminated and, therefore, the fiber laser is barely subjected to external mechanical actions. Single-mode lasing is naturally realized in fiber lasers. Because the absorption bands of rare-earth (Nd, Er, Yb, Tm, and Ho) ions overlap with emission lines of semiconductor laser diodes, the pumping by these lasers is efficient and femtosecond pulses can be obtained at comparatively low pump powers (< 1 W). The core of single-mode fibers is surrounded by a thick fused silica cladding providing efficient heat removal. This eliminates the necessity of designing special cooling systems. Fiber lasers take advantage of many elements developed for fiber-optic communication systems. These lasers prove to be efficient, compact, and convenient in operation.

Laser radiation has a broad spectrum, and passive mode-locking can be achieved by resorting to nonlinear optical rotation effect [21]. Femtosecond fiber lasers have surpassed in many respects conventional Ti:Sapphire lasers. The advantages of femtosecond fiber laser frequency combs are described in detail in paper [22]. All this led to the fact that femtosecond fiber lasers have been widely developed — until the onset of industrial production. At present, these lasers are manufactured by various companies, such as IMRA (USA), Menlo Systems (Germany), and Avesta (Russia), and are broadly exploited in various scientific fields.

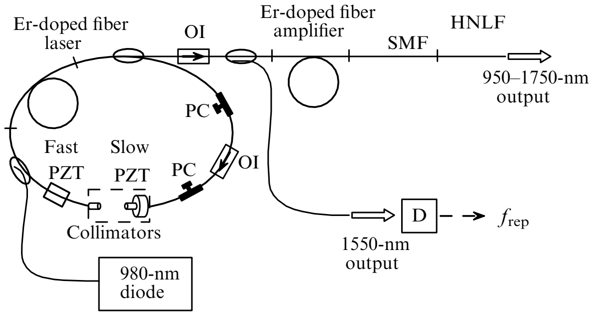

Figure 4. Femtosecond Er-doped fiber laser system [24]. PZT: piezoelectric element; OI: optical isolator; PC: polarization controller; SMF: single-mode fiber; HNLF: highly nonlinear fiber; D: detector.

Papers [23, 24] illustrate an example of applications of femtosecond fiber laser frequency combs, where a femtosecond Er-doped fiber laser was used in small optical clocks (stable at the 10^{-14} level) based on the He$-$Ne/CH$_4$ frequency standard (at a wavelength of 3.39 µm). It was mentioned in Section 2 that the comb offset frequency f_0 can be measured and controlled without making use of the complicated $f-2f$ interferometer method requiring octave spanning supercontinuum generation. The frequency f_0 can be measured with optical frequency standards, for example, the He$-$Ne/CH$_4$ standard. The comb can be stabilized by generating the difference frequency from comb modes f_n and f_m lying in different parts of the comb but separated by a frequency interval smaller than one octave. The generation can be produced in an appropriate nonlinear crystal, in particular, PPLN (periodically poled lithium niobate). As a result, a new comb is obtained, but now at the difference frequency, in which the optical standard frequency falls:

$$f_m - f_n = (mf_{\mathrm{rep}} + f_0) - (nf_{\mathrm{rep}} + f_0) = (m-n)f_{\mathrm{rep}} \,. \quad (3)$$

Thus, the frequency f_0 is eliminated and only f_{rep} should be controlled. This frequency was controlled in paper [24] by piezoelectric changing the cavity fiber length. Figure 4 illustrates the functional scheme of the setup. A 1.55-µm Er-doped ring laser was used with a pulse repetition rate controlled in the 62-MHz range by piezoelectric changing the cavity length in 'fast' and 'slow' channels. Two lens collimators were placed in the break of the fiber, the distance between them being controlled with a piezoelectric positioner. This provided a rather large but comparatively slow change in the cavity length. To produce rapid small changes in the cavity length, a piezoelectric element was directly glued to a fiber piece 5 mm in length. After amplification in an Er-doped fiber amplifier, supercontinuum generation was performed in an optical fiber with high nonlinearity. As a result, a frequency comb was obtained in the wavelength range from 950 to 1750 nm. Thus, a femtosecond fiber laser can be employed to build a compact and efficient system for generating broadband optical frequency combs (with the total pump power less than 1 W).

However, femtosecond fiber lasers generating frequency combs have, along with obvious advantages, an important drawback. Because optical fibers are essentially extended structures, it is difficult to diminish the cavity length to the size required to increase the pulse repetition rate above 1 GHz. Thus, femtosecond fiber lasers produced by Menlo Systems for spectral studies have a pulse repetition rate of 250 MHz. However, this disadvantage can be ingeniously surmounted by filtering comb radiation with the help of a Fabry–Perot interferometer having high transmission at resonance frequencies (modes) which are determined by the distance between interferometer mirrors. This allows one to filter transmitted radiation over the frequency. If the Fabry–Perot interferometer thickness is n times smaller than the laser cavity length, the interferometer will transmit comb lines spaced by a distance n times larger than the mode spacing in the comb (Fig. 5). The width of the transmission character-

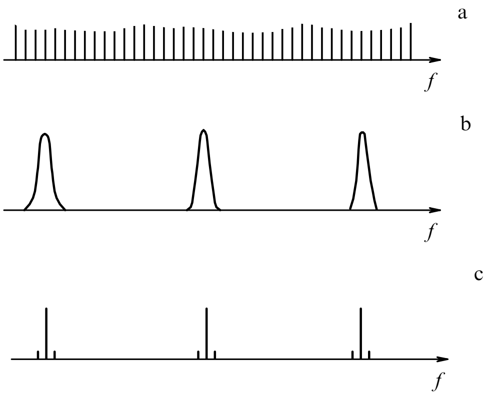

Figure 5. Filtration of the frequency comb spectrum with a Fabry–Perot etalon: (a) femtosecond laser spectrum, (b) Fabry–Perot etalon transmission, and (c) spectrum after filtration.

istic of the interferometer depends on the reflection coefficient of its mirrors. The specific features of filtration and the configuration of interferometer mirrors are described in Ref. [25]. The reflection coefficient of available mirrors is not sufficient for separating one mode of the comb. Because of this, filtration with the suppression of neighboring modes requires the utilization of two or even three etalons in tandem.

Femtosecond fiber lasers have another peculiarity that is very important for applications of frequency combs. As mentioned above, the increase in the repetition rate inevitably leads to a corresponding decrease in the pulse peak power. The filtration of the frequency comb also reduces the peak power by a factor of n, thereby reducing the efficiency of nonlinear conversions (supercontinuum and harmonic generation) required for obtaining a broad enough spectrum of the comb. To compensate for a decrease in the pulse peak power, pulse amplification is needed. The amplification can be efficiently performed in a fiber amplifier with the same fiber as in the laser. The standard efficient scheme for pumping an active double-clad fiber reliably provides an output power up to 10 W [7]. Pulse broadening during its propagation in an amplifying fiber with dispersion can be compensated for by connecting a piece of fiber with dispersion of the opposite sign. Such fibers can be manufactured at present. Thus, an OFC obtained in this way has a large mode spacing and high-power pulses required for second harmonic and supercontinuum generations. Figure 6 depicts changes in the comb spectrum during conversions of comb radiation in a femtosecond fiber laser.

4. Features of astronomical spectroscopy. Exoplanet searches

The unique feature of astronomical studies consists of permanent observations with accessible accuracy. This also concerns spectral measurements in which spectra recorded for long observation periods are compared. The spectrum of an astronomical object allows its velocity to be determined from the Doppler effect. A change in the spectrum in time reveals the dynamics of the astronomical object. In particular, the Doppler method for radial velocity measurements of stars is applied for the search for and investigations of planets revolving around other stars, so-called exoplanets.

Because we see planets in reflected light, the search for planets revolving around distant stars is performed by indirect methods, in particular, by the so-called transit method. The method is based on the observation of a star's small drop in brightness when the orbit of one of the star's planets passes ('transits') in front of the star. The observed star's brightness will regularly change with a period equal to the period of the orbital revolution of the planet around the star. The duration of the decrease in the star's brightness depends on the planet's transit time over the star's disc, while the amount of this decrease is determined by the planet's size. Obviously, this method requires a high accuracy in measuring the star's brightness during rather long measuring periods. The disadvantage of the method is obvious: it can be applied only to the search for exoplanets whose orbital plane (ecliptic) coincides with the direction to the star. Nevertheless, numerous exoplanets have been discovered by this method successfully applied during NASA's Kepler mission.

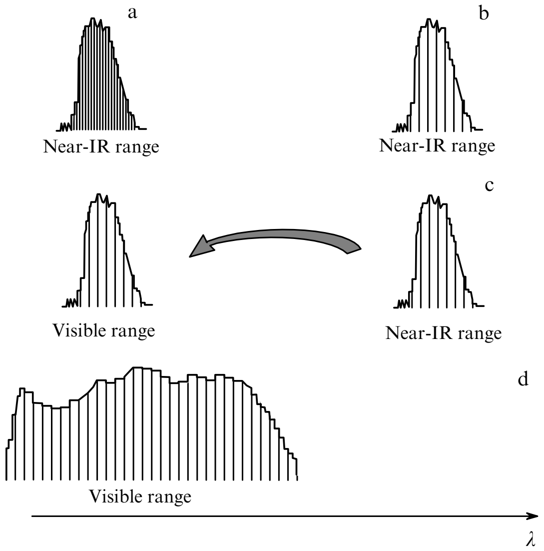

Figure 6. Modifications of spectra during conversions of femtosecond laser radiation. (a) Femtosecond fiber laser frequency comb in the near-IR range (≈ 1.1 μm, ≈ 1.54 μm) a few nanometers in width with the mode spacing of ≈ 250 MHz adjusted by an atomic clock. (b) An increase in the mode spacing to ≈ 18 GHz by filtering radiation with Fabry–Perot etalons. (c) Transfer of the spectrum to the visible range by the second harmonic generation. (d) Broadening of the comb spectrum over the entire visible range by supercontinuum generation.

Another method based on spectral radial velocity measurements of stars by the Doppler effect is also in use. A planet revolving around a star causes motion of the star itself with respect to their common center of mass (Fig. 7). The

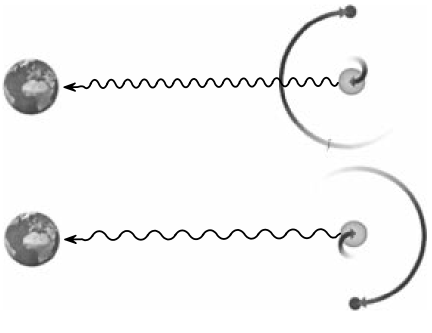

Figure 7. Light from a star with an exoplanet revolving around it. Under the action of gravity from the exoplanet, the star experiences small vibrational motions producing a Doppler shift of the spectrum.

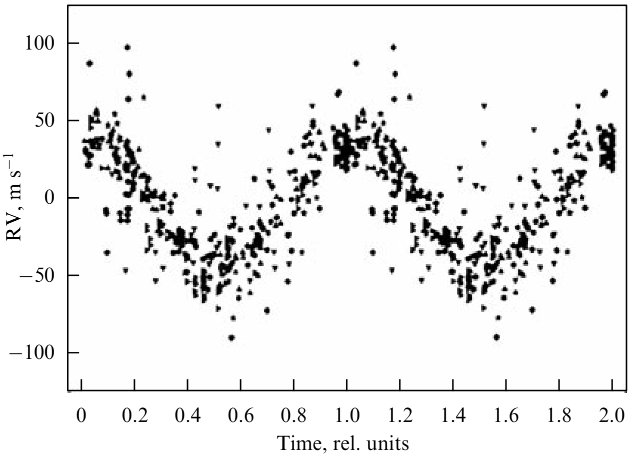

Figure 8. Periodical (592.9 days) variation in the radial velocity (RV) of the *bet Gem* giant star caused by the revolution of a Jupiter-mass planet [26].

relative change in the radial velocity of this periodic motion can be measured by the Doppler shift of the star's spectral lines. This method of studying exoplanets is illustrated by the data obtained by researchers at the Crimea Astrophysical Observatory and the Korean Institute of Astronomy and Space Research [26] (Fig. 8). The periodic change in the radial velocity of the giant star with a period of 592.9 days shown in Fig. 8 is caused by a Jupiter-like planet revolving around the star.

Note that changes in the radial velocity depending on the ratio of the planet's and star's masses are very small. Thus, the revolution of Jupiter around the Sun causes motion of the Sun with a maximum velocity of 12 m s^{-1} and period of about 12 years, while the revolution of Earth around the Sun causes a maximum Sun velocity of only 9 cm s^{-1} with a period of one year. Thus, to discover planets by Doppler shifts, it is necessary to measure rather small spectral shifts recorded for long periods of time. These measurements require high spectral resolution and high accuracy.

One of the impetuses for the discovery and investigation of exoplanets is the search for earthlike planets formed at a distance from a star at which the temperature on the planet's surface is favorable for the existence of liquid water (the so-called habitable zone). To find differences between gas giant planets such as Jupiter and Saturn and solid planets such as Earth and Mars, it is necessary to provide a measurement accuracy for Doppler spectral shifts at a level of a few cm s^{-1}, which corresponds to the frequency measurement accuracy at a level of 10^{-10}. Note that at present the accuracy of precision laser frequency measurement can be better than 10^{-15}. But this was achieved under laboratory conditions. However, in astronomy researchers have to deal with extremely weak sources, which are investigated with giant telescopes with very large mirrors providing the collection of light from such sources.

The search for and investigation of exoplanets is performed with unique spectrometers developed specially for this purpose, for example, the HARPS spectrometer (high accuracy radial velocity planet searcher) [27]. These spectrometers make use of large echelle gratings with the resolving power $R = \lambda/\Delta\lambda = \nu/\Delta\nu$ reaching 10^5. These are complex and bulky stationary devices with high mechanical and thermal stability. The spectrometer is communicated with a moving telescope through a special fiber-optic line. Single-mode fibers with a core 5–7 μm in diameter used in ordinary communication lines cannot be used here, because they cannot transmit a broad spectrum without distortions. In this case, special optical fibers are applied with a core of a special configuration a few hundred microns in diameter [28, 29], in which the mode structure of transmitted radiation and spectral distortions are completely eliminated.

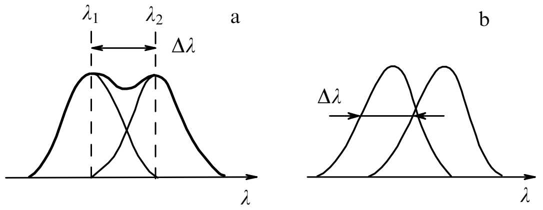

Figure. 9. Simultaneous (a) (the Rayleigh resolution) and separate (b) recording of two spectral lines.

The resolving power of a spectrometer is usually determined by its capability of resolving two adjacent spectral lines (the Rayleigh criterion) recorded *simultaneously* (Fig. 9a). This requires the *relative* calibration of the wavelength (frequency) range of the spectrometer. In measuring the Doppler shift, spectra are recorded *separately* for a long time (up to a few years!). If spectral lines are accurately and *absolutely* (which is very important) coupled to the wavelength (frequency) scale, the spectral shift of even relatively broad lines can be measured (Fig. 9b). Therefore, astronomical spectrometers for measuring rather small Doppler shifts should have, along with a high sensitivity and resolution, high-precision wavelength calibration coupled to the frequency standard (atomic clocks). Spectrometers are usually calibrated by recording emission from a spectral lamp, for example, a hollow-cathode lamp emitting spectral lines of gases filling the lamp. In particular, astronomical spectrometers are calibrated with a Th-Ar hollow-cathode lamp. The disadvantage of this method is the limited accuracy of measuring the line frequency (only to the seventh decimal place), the irregular distribution of spectral lines in the lamp emission spectrum, different intensities of the lines, and the influence of external conditions and lamp aging. Spectrometers can also be calibrated by narrow absorption lines. For example, data presented in Fig. 8 were obtained with the aid of iodine cells. However, the limiting precision of these spectral methods is about 1 m s^{-1}. A laser frequency comb, being a synthesizer of precision optical frequencies, shows the ability to replace the spectral lines of atoms and molecules. In fact, the frequency comb can be treated as an artificial atom with regularly arranged spectral lines. The utilization of frequency combs for spectrometer calibration eliminates disadvantages inherent in spectral lamps and iodine cells. Therefore, the quest for the application of laser frequency combs for high-precision wavelength calibration of astronomical spectrometers seems to be rather natural [30].

5. Calibration of astronomical spectrographs with laser optical frequency combs

The direct application of laser frequency combs for high-precision calibration of astronomical spectrographs involves considerable difficulties. First, no modern femtosecond lasers emit in the required visible spectral region (a Ti:Sapphire laser emits at ≈ 0.8 μm, whereas fiber lasers emit at ≈ 1.1 and

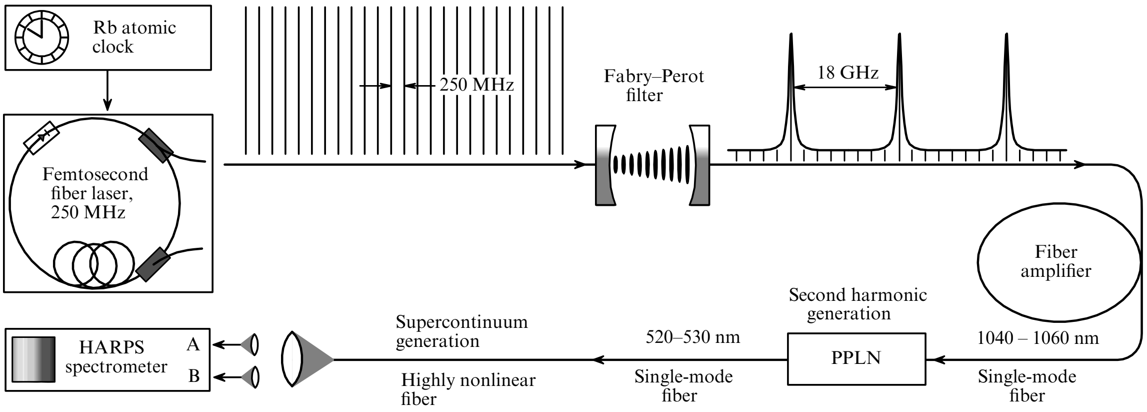

Figure 10. Conceptual schematic of an astronomical spectrograph calibrator.

≈ 1.5 μm). In addition, the width of the comb spectrum is not broad enough. Second, the mode spacing in the comb is equal to the pulse repetition rate and is usually about 100 MHz, which is determined by the laser cavity length (a few decimeters). For the resolution power of 10^5, the spectral resolution of the spectrograph in the visible range is about 6 GHz. This means that the spectral lines of femtosecond laser frequency combs will merge to produce a continuous spectrum. The first difficulty can theoretically be eliminated by nonlinear optics methods, such as second harmonic generation and supercontinuum generation. These methods can be quite efficiently applied because femtosecond pulses producing the frequency comb have, in principle, high peak power and intensity. As mentioned in Section 2, supercontinuum generation can produce an octave spanning comb. The second difficulty is surmounted by filtering the laser frequency comb with a Fabry–Perot etalon.

Laser methods for the wavelength calibration of astronomical spectrographs were developed by two research groups. The Hänsch group of the Max Planck Institute of Quantum Optics and Menlo Systems (Germany), in collaboration with the European Southern Observatory, are performing investigations on the 3.6-meter aperture telescope with the HARPS spectrometer ($R = 115{,}000$) at the La Silia Astronomical Observatory in Chile [31, 32]. The Diddam group of the National Institute of Standards and Technology (USA) performed studies at the MacDonald Observatory (University of Texas, USA) on the 9.2-meter aperture Hobby–Eberly telescope equipped with the near-IR Pathfinder spectrograph ($R = 50{,}000$) [33].

Figure 10 shows the conceptual schematic of the laser calibrator built by the German group. A Menlo Systems 1.1-μm femtosecond ring Yb-doped fiber laser has a pulse repetition rate of 250 MHz precisely stabilized with a piezoelectric controller by the reference frequency of Rb atomic clocks. After radiation filtering with Fabry–Perot etalons, the mode spacing in the frequency comb increases to 18 GHz. Losses due to filtration are compensated for by a Yb-doped fiber amplifier with dispersion compensation. The special double-clad pump configuration is used. Then, involving second harmonic generation in a PPLN crystal and supercontinuum generation in a highly nonlinear fiber, the spectrum is transformed to the visible range. As a result, a strictly regular and stable frequency comb spanning the total visible range is produced (Fig. 11). This system was sampled in astronomical studies. Astronomical spectrograph calibration with a laser frequency comb was demonstrated in a study of the radial velocity of a star with an exoplanet [33]. The results are presented in Fig. 12. Although the measurement accuracy in these first experiments was about 1 m s^{-1}, under laboratory conditions it was 2.5 cm s^{-1}, which suggests that the accuracy of astronomical measurements can be considerably improved.

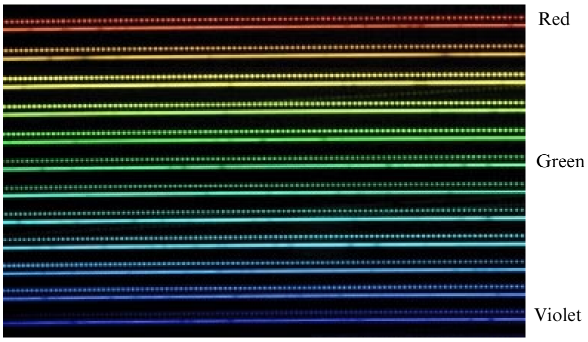

Figure 11. Calibrator comb spectrum recorded with a spectrograph.

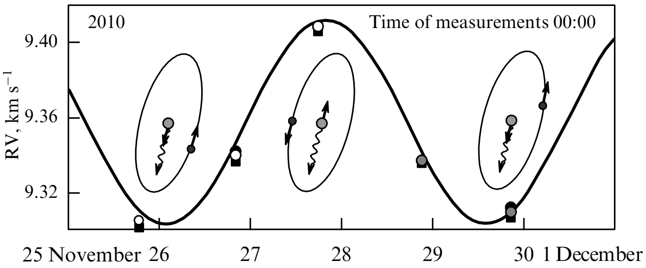

Figure 12. Measurements of the radial velocity (RV) of a star with an exoplanet [32].

The American group used a similar setup but with a Menlo Systems ≈ 1.55-μm ring Er-doped fiber laser [32]. The pulse repletion rate was increased to 25 GHz by radiation filtering with a Fabry–Perot etalon. As a result, a calibration frequency comb was produced in the near-IR range. The authors of Ref. [32] point out that there are significant reasons to perform measurements not only in the visible but also in the near-IR range. Obviously, the smaller the star, the stronger the Doppler shift which can be more simply discovered and measured. The M dwarf stars, in particular the M4 star studied in Ref. [32], only weakly emit in the visible spectral region but have a rather high brightness in the near-IR region. These stars compose more than 60% of the stars located in the region at a distance of 10 pc from Earth. Due to their small mass and weak brightness, the radial-velocity signal caused by an earthlike exoplanet located in the habitable zone with liquid water can be more than an order of magnitude stronger than a signal produced by Earth revolving around the Sun. The accuracy of frequency measurements under laboratory conditions reached 2×10^{-10} in the wavelength range from 1450 to 1630 nm, corresponding to an accuracy of radial-velocity measurements of about 6 cm s^{-1}. This accuracy in real astronomical measurements is ≈ 5 m s^{-1}.

In Russia, exoplanets are studied at the Special Astrophysical Observatory, RAS with the unique LAT (large azimuthal telescope) with a mirror 6 m in diameter. At present, a plan to significantly improve the measurement accuracy using the latest advances in fiber optics and laser technology is being discussed [34].

6. Possibility of other astrophysical studies

High-precision spectral measurements can be employed not only to search for and investigate exoplanets but also to examine other quite important astrophysical problems. Thus, high-precision measurements of the red shift of distant cosmic objects can be used in theory for the detailed study of one of the most important problems of modern science: the evolution of the Universe, in particular, to measure directly the acceleration of the expansion of the Universe. To do this, it is necessary to perform for a certain time interval precise measurements of the velocity of expansion of distant cosmic objects by the red shift of spectral lines and determine the change in the velocity (acceleration) for this time interval.

This idea was suggested in 1962 [35]. It was assumed at that time that the expansion of the Universe was decelerating due to universal gravity. However, estimates showed that spectral measurements with the accuracy that astronomical spectrographs had at that time would require observations for a few hundred years. In 2011, S Perlmutter [36], B P Schmidt [37], and A G Riess [38] were awarded the Nobel Prize "for the discovery of the accelerated expansion of the Universe through observations of distant supernovae." According to their investigations, this acceleration is a few centimeters per second for several years.

The accuracy of astronomical spectral measurements of the radial velocity by Doppler shifts, provided by laser methods for calibrating astronomical spectrographs described above, theoretically allows the direct measurement of the accelerated expansion of the Universe. It was proposed to measure radial velocities by radiation from quasars with a large red shift in the absorption lines of intergalactic clouds. For this purpose, the international CODEX (cosmic dynamics experiment) project is being developed [39, 40]. Researchers also intend to invoke the next generation giant telescopes with improved spectrographs precisely calibrated with the help of advanced laser systems.

Astrophysical investigations are being performed at the European Southern Observatory in Chile. The newest VLT (very large telescope) representing an array of four separate 8.2-meter aperture optical telescopes is equivalent to a telescope with a 16-meter mirror. A plan has been approved for the construction of the even larger E-ELT (European extremely large telescope) with a mirror 39 m in diameter, which consists of numerous hexagonal segments forming an adaptive optical system. Spectrographs with $R \approx 150{,}000$ in the wavelength range from 350 to 720 nm calibrated with a laser frequency comb will provide radial-velocity measurements with an accuracy of 1–2 cm s^{-1} for a few dozen years.

The main goal of the CODEX project is the first very high-precision direct measurements of the cosmic dynamics. This will be performed by observing many emission lines from quasars with Z from ~ 1.5 to ~ 4, including the Ly_{α} lines red-shifted to the visible range. Apart from measurements of the change in the expansion velocity of the Universe, a number of quite important scientific problems will be investigated:

(i) the discovery of earthlike exoplanets in the habitual zone of Sun-like stars;

(ii) the study of the genesis of the Milky Way;

(iii) the study of the interaction of galaxies and the intergalactic matter from which they formed;

(iv) the improved verification of the stability of fundamental physical constants.

Thus, work on the development of the latest telescopes with high-precision spectrographs will make a very valuable contribution to the important fields of astrophysics.

7. Femtosecond laser for space investigations

Femtosecond laser frequency combs successfully applied in astrophysical spectral measurements are also beginning to play an important role in other space studies planned for the near future [41, 42]. This requires the development of reliable femtosecond laser systems capable of withstanding overloads and vibrations during rocket launches and of operating at temperatures and in a vacuum in space under the action of cosmic radiation. In this respect, femtosecond fiber lasers are preferable due to the stability of their optical adjustment, the small size and weight, and the high efficiency.

Researchers at the Korea Advanced Institute of Science and Technology (KAIST) were the first to launch a femtosecond laser into space, which successfully operated in space for a year [43]. The laser was specially designed for operation in space; it was subjected to ground tests, and was sent into orbit on 30 September 2013. The laser setup weighing 2.5 kg withstood vibrations and overloads at a level of $10g$.

Figure 13 illustrates the traditional schematic of a femtosecond ring Er-doped fiber laser using a semiconductor saturable absorber (SA). The laser is pumped by a 980-nm,

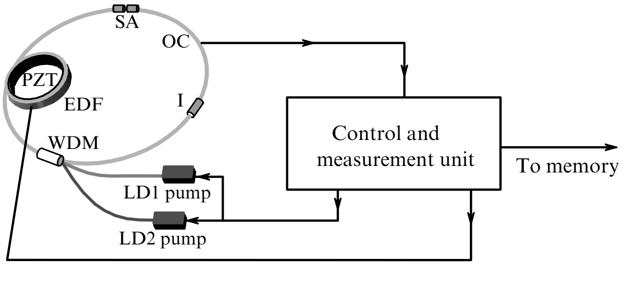

Figure 13. Schematic of a femtosecond fiber laser launched into space [43]. SA: semiconductor saturable absorber; PZT: piezoelectric controller of the fiber length; OC: outcoupler; I: isolator; EDF: Er-doped fiber; WDM: wavelength-division multiplexer for pumping; LD1 pump and LD2 pump: pumping laser diodes.

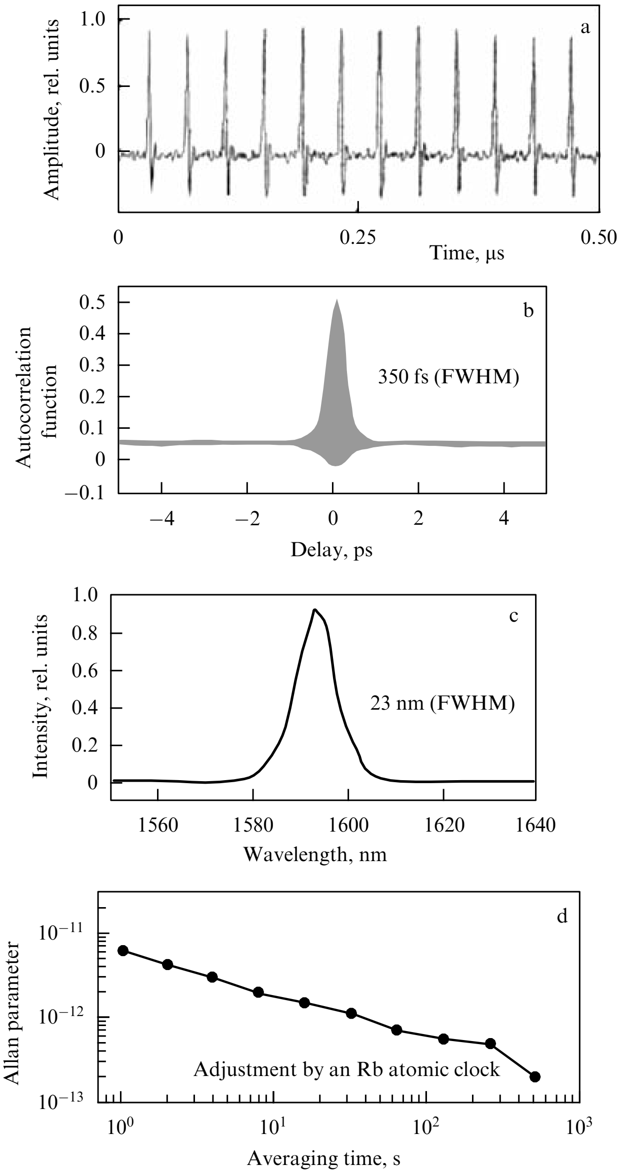

Figure 14. Laser parameters: (a) pulse train, (b) pulse duration characterized by the intensity correlation function, (c) spectrum, (d) frequency stability; FWHM: full width at half-maximum.

600-mW diode laser. The output power of the laser system is $\approx$ 14 mW. It decreased by 8.6% for one year under the action of cosmic radiation. The pulse repetition rate was controlled with a piezoelectric element. Figure 14 depicts the laser parameters. The pulse repetition rate was 25 MHz (Fig. 14a). Figure 14b shows the intensity autocorrelation function corresponding to a 350-fs pulse duration. The spectrum with the maximum at 1590 nm is presented in Fig. 14c. The frequency stability compared to the Rb:clock is characterized by the Allan parameter (Fig. 14d). Although these data are quite usual for such setups, the fact that they belong to a laser operating in space orbit is quite impressive!

8. Conclusions

A famous scientist in the field of laser physics, Arthur Schawlow, once said: “If you want to measure any physical quantity with a high precision, try to reduce its determination to the frequency measurement.” Astronomical measurements of the radial velocity of moving stars illustrate this idea very well. High-precision measurements of the motion of stars are reduced to the measurement of Doppler frequency shifts, the highest precision of these measurements being provided by the newest advances in laser physics. Of course, some specific features show themselves. Permanent measurements require reliable operational parameters of the equipment. No wonder that the newest advances of fiber optics are used in modern laser systems, because fiber lasers have high operational qualities. This is confirmed by the successful launching of a femtosecond laser into space and by its permanent operation in orbit.

An astronomical spectrograph calibrator based on a femtosecond laser is a rather complicated device. Therefore, its developers should directly participate in constant measurements at an observatory. In this way, they have the opportunity to perform investigations that are extremely important for fundamental science. There is reason to believe that investigations in this field are attractive for young researchers.

It should be noted that the development of laser systems for astrophysical studies does not require the construction of huge setups and the involvement of large research groups. These laser systems are quite compact and have excellent operational characteristics. The latest advances in the fields of laser physics, nonlinear optics, and fiber optics allow the successful development of such systems.

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