

# Fourier spectrometry and its applications

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*A short history and the principle of Fourier spectroscopy are presented. Some engineering problems, such as mirror motion irregularities during interferogram scanning, beam splitter construction and influence of water vapour, detector choice, sampling density, and scanning speed are discussed. Some ways to solve the problems are proposed. The advantages and disadvantages of Fourier spectroscopy with comparison to other spectroscopic techniques are presented. The applications in various domains with relevant references are mentioned. New trends in the Fourier spectrometry design are indicated. The works conducted in Poland are shortly described.*

## 1. Introduction

The relation between interferogram registered in interferometric system and spectral distribution of source radiation used for interferogram generation was observed for the first time by Foucault [1] in 1862 and utilised by Michelson<sup>1</sup> in 1891 [3].

At that time the main goal of experiments was to determine a structure of spectral lines only. In the experiment Michelson applied his interferometer with one of mirrors uniformly moved, and surprisingly, such a set-up is met in current Fourier spectrometers. In 1911 Rubens and Wood [4] used the interferometer consisting of two parallel plates with variable distance between them to determine far-infrared radiation spectrum of some bodies ( $\lambda \in 100\text{--}300 \mu\text{m}$ ).

Detailed description of the goals and experiments to be considered as the beginning of Fourier spectrometry is given in Ref. 5. However, at that time no computer was available, therefore any more complex calculations were extremely laborious. Probably, by this reason advantages resulting from the relation between interferogram and its Fourier transform could not be appreciated properly almost for a half of cen-

tury. Only in 1951 Fellgett, in his thesis [6], presented the first numerically Fourier transformed interferogram, which was obtained by scanning the fringes formed in air wedge between two glass plates. Fellgett demonstrated in his work, that in comparison to classical spectrometry a multiplexing spectrum registration introduces increase in a signal value of signal-to-noise ratio (feature known in literature as Fellgett's advantage). A little earlier, Jacquinet [7] had pointed out that interferometer has greater light efficiency than a conventional spectrometer of the same resolution (Jacquinet's advantage).

In 1957 the first conference in Bellevue (France) was devoted to Fourier spectroscopy [8], however, named yet as Interferometric Spectroscopy (Spectroscopie Interferentielle, in French). In 1961, J. Connes [9] published the thesis giving mathematical basis of Fourier spectroscopy. Some improvement in spectrometer design was introduced by her husband P. Connes (cat's-eye retroreflector, control of mirror displacements with a laser interferometer, and others).

The crucial date for the Fourier spectroscopy was elaboration of FFT algorithm by Cooley and Tukey [10] in 1965. Moreover, minicomputers came into practise; therefore Fourier spectroscopy could be applied to routine spectroscopic analyses. In IR region, difficulties connected with cooling of a detector and even the whole instrument (in the case of emissive spectrum) were reduced due to development of highly

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<sup>1</sup> Albert Abraham Michelson was born in 1852 in Strzelno, a town of Polish population, now in the territory of Poland (Pomerania). 4 years later his parents, Samuel Michelson and Rozalia Przytubska, with young son, emigrated to California [2].

sensitive detectors and active cooling systems (thermoelectric elements, Stirling refrigerator).

Since the middle of the sixties essential development of Fourier spectrometers was achieved. Many topical conferences were organised [11], topical numbers of scientific journals were issued [12], moreover, numerous monographs were published concerning the bases of Fourier spectrometry [see e.g. Refs. 13–16] and its applications [see e.g. Refs. 17 and 18] as well. Bibliography related to Fourier spectrometry problems includes already hundreds of papers. At last, since some time Fourier spectrometers, constructed for various applications, are available commercially [19].

## 2. Principle of Fourier spectroscopy

A general scheme of optical system of a Fourier spectrometer is shown in Fig. 1. The instrument contains the source of radiation  $S$ , the parabolic off-axis mirror  $M_c$ , the Michelson interferometer (the beam splitter  $B$  and two the planar mirrors  $M_1$  and  $M_2$ ), the focusing parabolic off-axis mirror  $M_r$ , and the detector  $D$ .

The radiation emitted by the source  $S$ , after collimation by the parabolic off-axis mirror  $M_c$ , propagates to a Michelson interferometer, and after that both interfered beams, reflected from both planar mirrors, are focused by the parabolic off-axis mirror  $M_r$  at the detector plane. The detector registers interferometric signals (interferogram) for various displacements of one of the planar mirrors of the interferometer. In Fig. 1 movement of the mirror  $M_1$  is denoted with the aid of arrows and the letters  $+z$  and  $-z$ .

The interferometric pattern in a Michelson interferometer arising at a focal plane of the mirror  $M_r$  does not depend on parameters of the source, i.e., its dimen-

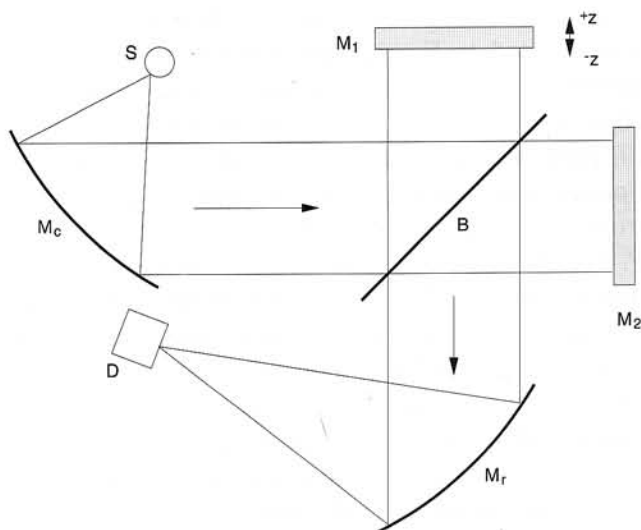


Fig. 1. Basic optical system of the Fourier spectrometer.

sions, intensity distribution in the source area, and the source position. These features represent essential advantages of a Michelson interferometer, especially when natural sources, like e.g., planet surfaces are used in place of the mirror  $M_c$  and the source  $S$  (Fig. 1). However, the interferometric pattern has the form of circular fringes (Haidinger fringes) and their radial density increases with increase in the shift  $z$  of the mirror  $M_1$ , measured from the mirror position, with null difference of the optical paths for both branches of the interferometer. For  $z = 0$  (null difference of optical paths) intensity distribution in the interferometric field is uniform. That is a problem for spectrometers with high spectral resolving power, when a large shift of the mirror is required. In this case the detector diameter should be sufficiently small or the focal length of the mirror  $M_r$  sufficiently large to detect proper state of interference only.

If the proper design is fulfilled, then we can analyse the result of interference in the middle of detector plane only. The demanded result can be described by the following equation

$$I(z, k) = I_1(k) + I_2(k) + 2\sqrt{I_1(k)I_2(k)} \cos(kz), \quad (1)$$

where  $k = 2\pi/\lambda$  is the angular wave number ( $\lambda$  - wavelength). The detector response is a result of the sum of interferometric signals for whole spectral radiation generated by the source  $S$  (multiplexing phenomena), this means that measurement of the interferogram is obtained by the following integration

$$R(z) = \int_{-\infty}^{\infty} I(z, k) R_k dk, \quad (2)$$

where  $R_k$  is the spectral sensitivity of detector.

The intensities  $I_1(k)$  and  $I_2(k)$  of interfering waves reflected from the first and second mirrors, respectively, depend on the coefficient of spectral transmittance  $\tau_i(k)$  ( $i = 1, 2$ ) of both channels of the spectrometer, therefore we can write

$$I_i(k) = I_0(k)\tau_i(k), \quad i = 1, 2 \quad (3)$$

where  $I_0(k)$  is the spectral intensity (radiance) generated by the source  $S$  and

$$\tau_i(k) = \tau_c(k)\tau_{M_i}(k)\tau_r(k), \quad i = 1, 2 \quad (4)$$

$\tau_c(k)$  is the coefficient of spectral reflection of the mirror  $M_c$ ,  $\tau_{M_i}(k)$  is the coefficient of spectral transmission

of both branches of the Michelson interferometer;  $\tau_r(k)$  is the coefficient of spectral reflection of the mirror  $M_r$ .

Denoting

$$f(k) = I_0(k) \sqrt{\tau_1(k)\tau_2(k)} R_k, \quad (5)$$

according to equations (1–3) we have

$$R(z) = C + FT^{-kz} [f(k)] + 2\pi FT^{kz} [f(k)], \quad (6)$$

where

$$C = \int_{-\infty}^{\infty} [I_1(k) + I_2(k)] R_k dk \quad (7)$$

is the constant and  $FT^{-kz}$ ,  $FT^{kz}$  are the operators of Fourier and inverse Fourier transformations, respectively.

If the interferogram could be known in an unlimited range of the mirror shift [ $z \in (-\infty, \infty)$ ], then according to Eq. (6) by calculating the Fourier transform of  $R(z)$  three separate elements could be obtained, namely  $C\delta(k)$ ,  $f(-k)$  and  $f(k)$ . Using such a theoretical procedure, knowing spectral transmission of both channels of the spectrometer, i.e., coefficients  $\tau_1(k)$  and  $\tau_2(k)$  as well as the spectral sensitivity  $R_k$  of detector, the spectral radiance  $I_0(k)$  is determined on the basis of Eq. (4). The metrological problem can be inverted. For the known spectral radiance  $I_0(k)$  of the source (usually for IR region a black body is used) the spectral sensitivity of the detector is found. Moreover, for all known spectral parameters of the spectrometer, the spectral transmission of any element set between the mirror  $M_c$  and the Michelson interferometer, or between the interferometer and the mirror  $M_r$ , is measured. In the same way as for the source radiance determination, the spectral emission of any body can be determined by introducing the light flux of the studied body directly into the interferometer. It is worth remarking that in the considered theoretical procedure, in all cases, the measurement is accomplished with precise determination of spectral parameters of the spectrometer and precise calculation of the Fourier transform calculation.

However, in real cases the measurement of the detector response  $R(z)$  occurs in the finite range of the mirror displacement only [ $z \in (-z_{\max}, z_{\max})$ ]. By definition, let  $A(z)$  be a function equal to zero outside the measurement range of  $z$ . In the simplest case  $A(z) = 1$  for  $z \in (-z_{\max}, z_{\max})$ , and  $A(z) = 0$  outside of this range. For the last solution one can speak about a nonapodized interferogram. As it can be seen later the

choice of the apodization function, gradually decreasing with increase in  $|z|$  improves the measurement possibility. In other words, in place of  $R(z)$  theoretically determined in the unlimited range of  $z$ , in real cases the apodized interferogram  $R'(z)$  is known and described by the following relation

$$R'(z) = R(z)A(z) \quad (8)$$

The Fourier transform of the product leads to convolution of the Fourier transforms of the components. Therefore, taking into account result (6) we can write

$$FT^{-kz} [R'(z)] = Ca(k, z_{\max}) + [f(-k) + f(k)] \otimes a(k, z_{\max}), \quad (9)$$

where the monochromatic response of spectrometer (function named also as instrument line shape) is given by the relation

$$a(kz_{\max}) = FT^{-kz} [A(z)] \quad (10)$$

In relation (9), which is solved numerically, three components can be separated with the aid of a computer program. It is possible due to usually narrow band of the monochromatic response  $a(kz_{\max})$ . The third component

$$f'(k) = a(k, z_{\max}) \otimes f(k) \quad (11)$$

is the quantity determined during the measurement. According to (11) the demanded function  $f(k)$  is spread by a monochromatic response. The obtained result cannot be identical with the real quantity due to a finite range of mirror displacement of the spectrometer.

### 3. Resolving power of the spectrometer

The measure of the spectrometer resolving power is a minimum difference expressed in wave numbers of two monochromatic responses to be taken as separate. The criteria commonly used in optics, for example the Rayleigh criterion, are rather conventional. Resolving power determined on the basis of any criterion indicates instrument capabilities only. Resolving power of a real instrument, besides the monochromatic response, depends on many other factors, therefore it must be determined experimentally.

Let a source emit two sufficiently close spectral lines for  $k = k_1$  and  $k = k_1 + \Delta k$ . Moreover, let both lines be of equal intensities. Due to the small difference  $\Delta k$  between both lines the equality of spectral

transmission of both lines in both channels of the spectrometer can be assumed. For these lines, by the same reason, equal detector sensitivities can be taken. According to Eq. (5) and (4), in place of  $I_0(k) = \delta(k - k_1) + \delta[k - (k_1 + \Delta k)]$  we can write

$$f_{2\delta}(k) = \delta(k - k_1) + \delta[k - (k_1 + \Delta k)]. \quad (12)$$

Taking into account Eq. (12), relation (11) becomes the sum of monochromatic responses

$$f'_{2\delta}(k) = a(k - k_1, z_{\max}) + a[k - (k_1 + \Delta k), z_{\max}]. \quad (13)$$

In the case of nonapodized interferogram [ $A(z) = 1$  for  $z \in (-z_{\max}, z_{\max})$ ,  $A(z) = 0$  for  $|z| > z_{\max}$ ] the monochromatic response function is

$$a(k, z_{\max}) = \text{sine}(kz_{\max}) \quad (14)$$

where  $\text{sine}(x) = \sin x/x$ . This means that on account of relation (13) we have

$$f'_{2\delta}(k) = \text{sine}[(k - k_1)z_{\max}] + \text{sine}[k - (k_1 + \Delta k)]z_{\max}. \quad (15)$$

According to primary criterion formulated by Rayleigh both monochromatic responses are resolved if the function  $f'_{2\delta}(k)$  in its centre of symmetry takes the value 20% smaller with comparison to its maximum. Additionally, the criterion formulation can be expressed by the following relation

$$f'_{2\delta}(k_1 + 0.5\Delta k_g) = 0.8f'_{2\delta}(k)_{\max}. \quad (16)$$

Such a situation is shown in Fig. 2a. The individual monochromatic responses are denoted by dashed lines and the spectral intensity distribution  $f'_{2\delta}(k)$  by the solid line. The limiting value  $\Delta k_g$  fulfilling the relation (16) and determined numerically is given as  $\Delta k_g z_{\max} \approx 1.5\pi$ . To simplify our considerations the notion of angular wave number  $k$  has been used. However, in spectroscopy the basic notion is somewhat different, namely the wave number  $1/\lambda = k/(2\pi)$  expressed in  $\text{cm}^{-1}$ . Therefore the resolving power for the wave number is given by the relation

$$\Delta\left(\frac{1}{\lambda}\right)_g = \frac{0.75}{z_{\max}}. \quad (17)$$

According to relation (17) an evident conclusion can be formulated: the construction of the Fourier spectrometer with high resolving power requires sufficiently large displacement of one of mirrors of the Michelson interferometer.

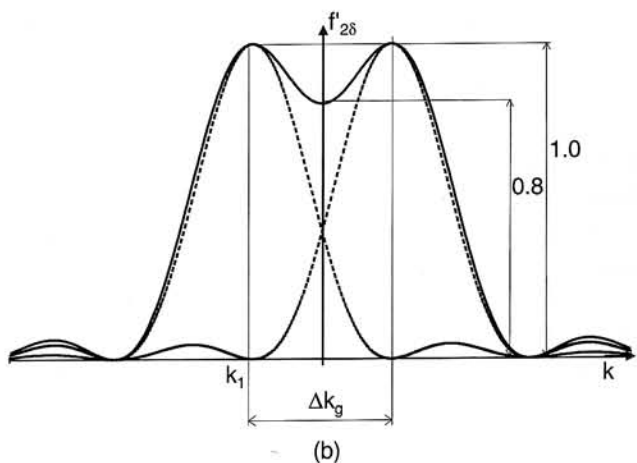
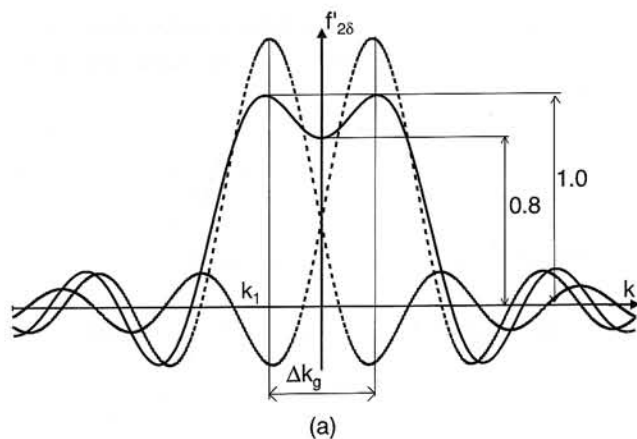


Fig. 2. Resolving power in the case of nonapodized (a) and apodized (b) interferograms.

As it is seen in Fig. 2a, the individual monochromatic responses, besides the main maximum, have sidelobes of significant intensities with comparison to their maximum (over 20%). Such a phenomenon can be harmful when two lines of different intensities are studied. The intensity value of the weak line can be comparable or even less than the sidelobe intensity of the strong one, and in this case the distinction of the weak line becomes impossible. Moreover, the sidelobes would be interpreted as false lines. To avoid such a situation the apodization of the interferogram is applied. The function  $A(z)$  in Eq. (8) should gradually decrease with increasing  $|z|$ . There are various apodization functions used like cosine, trapezoidal, Gaussian, etc. [14,20]. The most common function is triangular one (linearly decreasing up to zero at the edges of the interferogram), for which [14]

$$a(k, z_{\max}) = \text{sine}^2(0.5kz_{\max}). \quad (18)$$

Now, for the Rayleigh criterion we have  $0.5 \Delta k_g z_{\max} = \pi$  and



$$\Delta\left(\frac{1}{\lambda}\right)_g = \frac{1}{z_{\max}} \quad (19)$$

According to equations (17) and (19) the application of the apodization triangular function reduces the resolving power of the spectrometer with comparison to the case of nonapodized interferogram due to a larger width of the main maximum measured at half peak intensity. But simultaneously it reduces the height of sidelobes to 4.7% of the peak intensity (Fig. 2b).

It is worth to remark that any interferogram, apodization achieved by decreasing the intensity at the interferogram edge, leads to two opposite tendencies presented above. Any improvement in the monochromatic response by decreasing the sidelobe influence reduces the spectrometric resolving power. Fortunately, apodization is introduced numerically. For one measured interferogram various spectrograms can be determined for various functions of apodization. The comparison of the spectrograms obtained in such a way may be useful.

#### 4. Engineering problems

The design and construction of Fourier spectrometer, especially with high resolving power, require overcoming many mechanical, electronic and optical technological difficulties. The requirements related to some of them are extremely high. Despite an appreciable price the advantages of Fourier spectrometers resulting from their flexibility are so significant that they find more and more common applications in chemistry, atmospheric and cosmic studies, optical measurements, and others. Individual engineering problems will be shortly discussed with some ways to solve the problems.

##### Mirror motion irregularities

The optical configuration of the Michelson interferometer should be so adjusted, that two interfering planar waves emerging from the interferometer will be ideally parallel. Permissible deviation is so small and, moreover, fulfilled for a whole range of interferometer mirror movements, that the word ideal is not an exaggeration. Using an approximate method to estimate the interferometric error only the assumption of  $0.1 \lambda$  as the permissible error of the wave deviation can be made [21]. If the diameters of interferometric beams are denoted by  $D$ , then the

maximum tilt error of the movable mirror is given by the equation

$$\Delta\alpha_g = 0.1 \frac{\lambda}{D} \quad (20)$$

For rather small diameter  $D = 20$  mm and typical short wavelength edge of the spectral range  $\lambda_{\min} = 2 \mu\text{m}$ , the value of  $\alpha_g$  is equal to 2 s of arc. To fulfil such an exact condition various technical remedies are used. For small diameters  $D$  cube corners are applied [22] (Fig. 3), for larger ones –cat's eye retroreflectors (Fig. 4) [23]. The common feature of both solutions is the independence of returning waves of the tilt of the elements. The disadvantage of the cat's eye retroreflector is elongation of optical system. In case of large diameter  $D$ , three additional interferometers can be applied. The interferometers are set at three points of plane mirror to control its angular position with the aid of linear piezoelectric transducers.

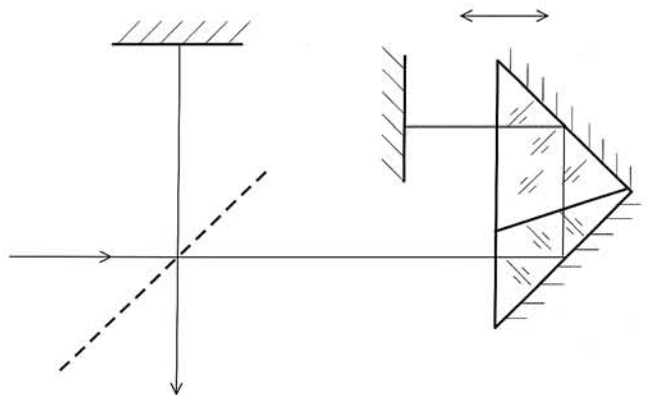


Fig. 3. Interferometer with moving cube corner prism and two planar mirrors.

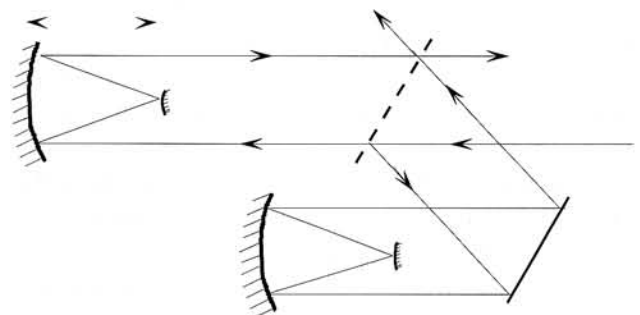


Fig. 4. Interferometer with two cat's eye reflectors. One of the reflectors is moved.

## Temperature instability

Temperature changes of environment and heat internal sources (laser, electronic elements, driver controlling the mirror, and others) change the temperature distributions in the instrument area, what leads to a misalignment of the interferometer. Besides temperature stabilisation in internal area of the interferometer, to decrease influence of remaining temperature changes the compact design of the interferometer should be applied [24]. This means that the beam splitter, mirrors and retroreflectors should be mounted in a common assembly (Fig. 5). All elements of the assembly should be made of the same material (extra-fine steel), including all screws. Lapping of all mechanical elements before their mounting is indispensable.

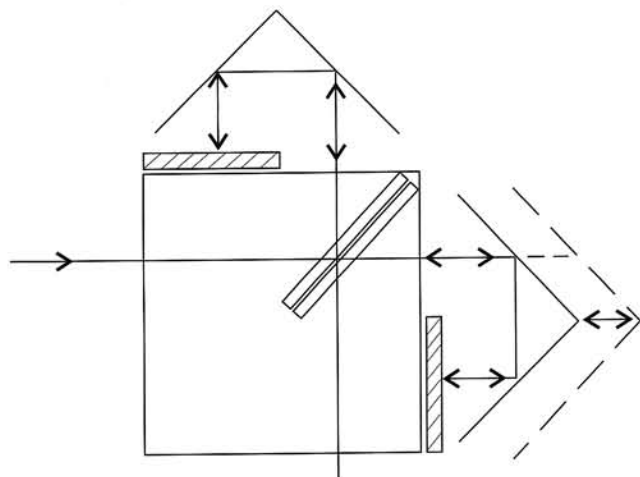


Fig. 5. Compact design of the interferometer with two cube corner reflectors. One of the cube corner prism is moved.

## Beam splitter

The optical path difference between both branches of the interferometer should be independent of wavelength. This means that lengths of wave paths in both branches for materials with large dispersion should be equal. For this purpose the beam splitter is equipped with a compensator (Fig. 6) made of the same material as the plate with a semitransparent film (Ref. 14, Chapter 9). The influence of air dispersion remains which is usually too weak to be taken into account.

In the interferometer, two interfering waves reflect from the semitransparent surface and pass through it in both cases only once. The reflection from remaining surfaces of the beam splitter generates parasite ra-

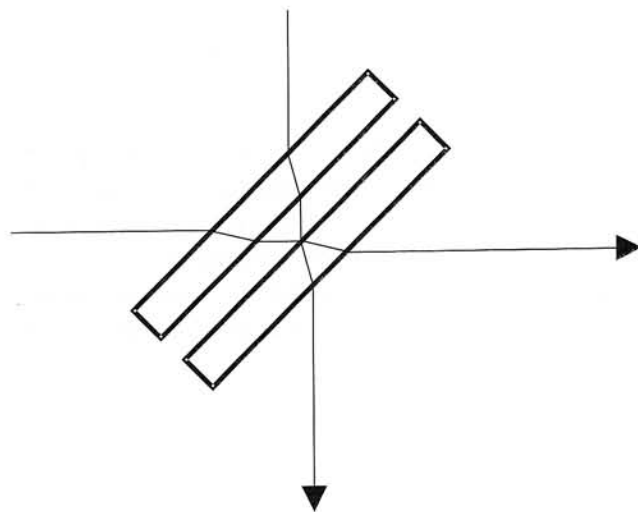


Fig. 6. Beam splitter consisting of two plates (compensator and beam dividing plate).

diation disturbing the required interference result. To remove the parasite radiation out of instrument all beam splitter surfaces are mutually tilted by small angles. In this case a thickness and wedge angles of both plates have to be equal because of influence of their dispersion. Moreover, wedge directions of plates should coincide.

For the spectral range  $\lambda \in (2, 16 \mu\text{m})$  the plates of the beam splitter are usually made from KBr (refractive index  $n \approx 1.53$ , high transparency) sensitive to humidity (Ref. 25, Vol. 3, Chapter 1). The semitransparent surface is covered by the films with germanium, giving almost uniform transmittance and reflectance in a large spectral range of IR (Ref. 14 Chapter 9). Some disadvantage of such a solution is the opacity of germanium in visible range, preventing visual instrument adjustment. Moreover, the interferogram is detected as a set of samples. The mirror positions for the registered sample signals are determined using additional Twyman-Green interferometer, which is based on the elements of the Michelson interferometer described earlier (see Fig. 1). This means that the beam splitter should be designed to divide the radiation used by two interferometers simultaneously. Usually, the second interferometer operates with the red line of He-Ne laser, fully absorbed by germanium film. To fulfil the condition of division for two different spectral regions, the active area of the beam splitter is divided geometrically into two independent parts with different semitransparent films.

It is worth to remark that technologically the beam splitter belongs to the most complicated components of the spectrometer.

## Parabolic mirrors

Focusing features of optical elements should be independent of wavelength. This is possible for mirrors only. There are two solutions: axial parabolic mirrors for cat's eye retroreflector or off-axis parabolic ones. The first solution requires a large area along the mirror axis. In the second case the off-axis parabolic mirrors are more difficult to manufacture.

## Detectors and cooling process

Thermal and quantum detectors are used. The detectors of the first group respond to temperature changes induced by infrared signal. They can be used at room temperature with no cooling. Low noise level and wide spectral range are their advantageous properties. However, limited sensitivity and long response time require low frequency modulation. Quantum detectors measure the signal energy of excited electrons in the detector material. Due to high noises generated at room temperature they have to be cooled, what simultaneously increases the detector sensitivity (Ref. 15, Chapter 4). The most commonly used quantum detectors are manufactured on the base mercury cadmium telluride (HgCdTe) ternary alloys.

For commercial spectrometers, devoted to the studies of the absorptive spectrum, the detectors cooled using micro Peltier termoelements (temperature about 200K) are sufficient [26]. Other applications, like measurements of emissive spectrum, require operation in the temperature of liquid nitrogen, or even below using Stirling refrigerator (Ref. 27, Chapter 15). The last solution is especially devoted to space studies.

## Sampling density

The interferogram is detected as a set of samples. According to, equation (8), in place of  $R'(z)$  the quantity is measured as

$$R'_s(z) = R'(z) \sum_m \delta(z - m\Delta z), \quad (21)$$

where  $\Delta z$  is the interval between adjacent samples.

According to the considerations of Chapter 2, see especially relations (9–11), Fourier transformation of  $R'_s(z)$ , for one component of (9) with the demanded function  $f(k)$ , gives

$$f'_s(k) = \sum_m f'(k - mk_0), \quad (22)$$

where

$$k_0 = \frac{2\pi}{\Delta z}. \quad (23)$$

The result of sampling gives the multiplied function  $f'(k)$  with the period  $k_0$ . The sampling density should be so high that the adjacent functions  $f'(k)$  do not mutually overlap.

Let the function  $f'(k)$  be defined in the region  $k \in (k_{\max}, k_{\min})$ . Separation of the functions  $f'(k - mk_0)$  is possible if

$$k_{\max} - k_{\min} < k_0 = \frac{2\pi}{\Delta z}. \quad (24)$$

Because  $k_{\max} = 2\pi/\lambda_{\min}$ , and  $k_{\min} = 2\pi/\lambda_{\max}$ , and if we assume for simplicity that  $\lambda_{\max} \gg \lambda_{\min}$ , then in place of the inequality (24) a simple relation can be written as  $\Delta z < \lambda_{\min}$ . In practice, to avoid the influence of any signal jitters, more restrictive condition is taken, i.e.,

$$\Delta z < \frac{\lambda_{\min}}{2}. \quad (25)$$

Using the interferometer with a He-Ne laser to control mirror displacements, signal samples are usually registered with the interval  $\Delta z = \lambda_{\text{He-Ne}} = 0.633 \mu\text{m}$ . Such a configuration can be applied to the IR spectral range  $\lambda_{\min} > 1.3 \mu\text{m}$ . For a spectrometer with the resolving power of  $0.1 \text{ cm}^{-1}$ , according to Eq. (19), we have  $z_{\max} = 10 \text{ cm}$ . In this case, recording only half of the interferogram, the number of samples is considerably large ( $z_{\max}/\lambda_{\text{He-Ne}} \approx 158028$ ). The registration of the whole interferogram requires two times larger number of samples. However, there are spectrometers with the resolving power 10 times higher [28], and even more. Accordingly, data processing in Fourier spectrometry requires fast analog-digital conversion and fast computers with a large memory.

An influence of registration errors is a software problem and it will not be presented here. It includes the issues of irregularities of the individual intervals, precision of data processing as well as the problem of asymmetry of interferograms related to residual dispersion and other errors non mentioned here, but requiring, so-called, phase correction procedures. Such problems are widely discussed in literature [14].

## **Influence of water vapour**

As it has been mentioned earlier some optical materials used in IR region have a weak moisture resistance (KBr, for example). Moreover, water vapour, and water in general, has strong absorption bands in this region [29] (band of 5–8  $\mu\text{m}$ , for example). This restrains the possibilities of measuring other components, such as contained in water solutions. Besides sealing the instrument and simultaneous application of water vapour absorbing medium inside, the spectral analyses in other spectral regions or even on spectral absorptive water background are indispensable.

## **Scanning speed**

The design of electronics system depends on velocity of moving mirror. For slow displacement with the signal modulation frequency even lower than a few Hz, a chopper is used to eliminate noise. For accurate interferogram sampling the positions of the moving mirror should be monitored by secondary fringe-referenced device. Due to conjugation with the interferometer drive mechanism, the interferogram can be sampled at equal intervals, independently of some irregular velocity of the moving mirror. For interferometers of low resolution it is sufficient to use the stepping-motor drive, without any monitoring of the mirror positions. The movable mirror is held stationary at each sampling position and then moved rapidly to the next one. For higher resolution the servomechanism has to be used to actuate the mirror after every step controlling by an additional laser reference interferometer.

The rapid-scanning method increases modulation frequency of registered signals what enables their amplification without chopper use. To increase the signal/noise ratio, the signal-averaging techniques must be used. Moreover, all corresponding data points in each successive scan step have to be digitised at exactly the same retardation value. In this case an additional laser fringe-referenced interferometer becomes indispensable. The main advantage of a rapid-scanning spectrometer, with comparison to slow-scanning one, is reduction of measurement time.

## **5. Advantages and disadvantages of Fourier spectrometry**

The proprieties are listed with reference to other spectrometric measurement methods.

### **Advantages:**

- higher light efficiency (Jaquinot advantage);
- higher signal-to-noise ratio, multiplex operation ( Fellgett advantage);
- natural co-operation with computers and computer networks;
- interactive possibilities of measured interferogram processing (noise removal, apodization changes, phase correction);
- interactive transformation of calculated spectrum (compensation of linear change, differentiation and deconvolution of spectral distribution, fitting spectral distributions to spectral data library).

### **Disadvantages:**

- measurement time (from a few to dozen and so seconds) required to measure interferogram and calculate FFT;
- high technological requirements and resulting relatively high price of a spectrometer.

## **6. Fourier spectrometry applications**

Fourier transform spectroscopy is a widely used technique to measure spectral transmission, reflection and emission of solids, liquids and gases especially in infrared and far infrared spectral ranges (Ref. 15, Chapter 3). Every domain, such as chemistry, space studies, optics and other fields of application using the Fourier spectrometry technique has elaborated own methods and instruments for its specific requirements. Below, the application domains, their goals, and eventually some performance data will be mentioned. In some cases general reviews in scientific journals or conference papers will be quoted as well to provide more detailed information.

### **Analytical chemistry**

Determination of absorptive spectra of various substances as well as spectral emissivity of materials to establish their chemical constitutions [30]. The applications concern inorganic [31] or volatile organic compounds [32], polymer materials [33], refined petroleum products [34], even semiconductor materials [35] and many others. To determine a gas phase reaction of physically and/or chemically unstable molecules air is drawn into the absorption cell [36].

### **Atmosphere and environment monitoring**

The measurements concern especially determination of pollutant concentration in air, so-called, atmo-



spheric chemistry [36]. The studies can be conducted from stable [37] or mobile [38] laboratories. Observations of effluence of small building smokestacks [39] are performed. Moreover, using two in-parallel located monitoring systems the changes of plume constituents under wind influence can be determined [40]. Fourier spectrometry can be useful to study the greenhouse effect [41].

### Remote sensing from spaceborne spectrometers

Persky in his excellent review [18], describing in detail 23 systems performed up to 1995 in various countries, presented goals and some measurement results, as well as technical parameters of instruments and their designs. He distinguished four basic categories of the remote sensing methods:

(a) sounding of atmospheric temperature and water vapour altitude profiles, atmospheric process studies, and surface composition of the Earth,

(b) environmental monitoring of the Earth's greenhouse gases, ozone, pollutants, etc.,

(c) surface and atmospheric composition studies of planets other than Earth,

(d) military purposes (missile defense system).

Many references cited in the review deserve particular notice for the readers interested in them. Similar role to Persky's review fulfils the earlier monograph [17]. For extreme weak concentration of gases (pollutants, for example) absorptive spectra are studied with the Sun as a radiation source [42].

### Biological studies

In the eighties Fourier spectrometry revolutionised the field of biomedical infrared spectroscopy [43] due to its advantages [44]. Extremely high quality infrared spectra of animal and human tissues and cells allow us to analyse their structural and dynamic properties at molecular level [45].

### Applications in optics

Measurements of spectral transmission of filters [46], spectral diffusion and specular reflection [47], spectral emission of materials at high temperatures [48] and in consequence temperature [49] as well as optical constants of solids, liquids and gases [50] belong to natural applications of Fourier spectrometry. The application of the attenuated total reflection (ATR) method allows the surface studies of the solids (Ref. 15, Chapter 3). Monitoring of thin films used, e.g., in semiconductor device manufacturing is the

same natural problem of Fourier spectrometry [51]. It is interesting that FTIR spectrometry can be integrated with polarisation methods to determine properties of electro-optical materials [52] and the dielectric function of layered materials [53].

### Micromasurements

Good examples of the possibilities of new FTIR method are determination of molecular composition of a single suspended microparticle [54] and integrated dust analysis by observation of isolated particles or particle clusters [55].

## 7. Current trends in Fourier spectrometry

Contemporary the Fourier spectrometry is extensively developed technique. As usual, a tendency to improve its possibilities will never disappear. A study of time-dependent phenomena [56], the enlargement of spectrum to visible and UV ranges [57] and field spectrometry [58,59] consisting in registration of some interferograms, simultaneously by focal-plane array detector, are natural steps. Similar nature of such tendency is reduction of interferogram registration time to a fraction of a second [60], and even millisecond [56], to follow-up, for example, chemical reactions [61]. However, a tendency to improve some parameters is rather accompanied by opposite changes of other parameters, e.g., time reduction is accomplished due to decrease in spectroscopic resolution, and almost always with cost rise.

A cost problem is the essential one. Simplification of the moving mirror system [59,62] is one of the propositions to remedy it. More sophisticated method is registration of the whole interferogram with the aid of a matrix detector [63,64], however, with considerable decrease in instrument resolution, related to limited number of array-detector pixels.

To avoid the vibration influence, upon mirror movement, the interferometer basing on fibre optics can be used [65]. The path difference scan is generated by stretching a fibre or changing its temperature. Due to an influence of dispersion, the fibre optic spectrometry gives promising results in a narrow spectral range only.

## 8. What is in Poland?

Besides a wide use of commercial spectrometers in various scientific laboratories, original designs are developed in the co-operation between the Space Research Centre (the Polish Academy of Sciences) and

the Institute of Micromechanics and Photonics (the Warsaw University of Technology).

One of designs, sponsored by the State Committee for Scientific Research and managed by the Space Research Centre, concerns the atmosphere studies from the satellite. The spectrometer is devoted to the CESAR project (the Central European Satellite for Advance Research), which has been established by the countries of the Central European Initiative involving Italy, Austria, Czech, Slovak Republics, Hungary, and Poland. The project managed by the Italian Space Agency is a result of promotion of co-operation in the space programme. The spectrometer measuring the absorptive spectra with the Sun as a radiation source has to determine the weak concentrations of pollutants and their spatial distributions using the wavelength band 2–16  $\mu\text{m}$  with spectral resolution 0.1  $\text{cm}^{-1}$  and for the altitude range between 10 km and 100 km ( $\pm 1\text{km}$ ) with vertical spatial resolution  $\sim 2$  km.

The second stationary instrument has been designed in the Optical Engineering Division of Institute of Micromechanics and Photonics in co-operation with Space Research Centre. The project is sponsored by the Warsaw University of Technology within the framework of the University Priority Program of Photonics Engineering. The spectrometer measures the absorptive spectra of atmosphere in the spectral range 3–12  $\mu\text{m}$  (resolving power better than 1  $\text{cm}^{-1}$ ) to determine concentrations of pollutants. The radiation emitted by a ceramic radiator, located close to the instrument, is focused at a spherical mirror plane, distanced at 20 m from the spectrometer. After reflection from the mirror, the transmitted radiation is introduced into the spectrometer. In this way the absorption path in the atmosphere is two times longer than the distance between the mirror and the instrument.

At present, both spectrometers are tested. The detailed information about the instrument designs and the study results will be published later.

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