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Interferometer with Rotating Plate: Fundamentals

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Abstract. Technical parameters of base elements and optical scheme of the interferometer with a rotating plate is considered. The calculation of the optical scheme is carried out by ZEMAX. Spherical aberration values and the energy collection efficiency on photodetector are optimized during parameter calculation. The distortion pattern shape of instrumental function in the spectra due to the nonlinear dependence of the optical path difference in the interferometer beam from the rotation angle of the plate is investigated. Mathematical modelling results of distortions in restored spectrum for a ZnSe plate are represented. The possibilities of digital filtering of spectrum via convolution interferogram with apodization function are investigated.

Introduction

Nowadays Fourier transform spectrometers (FTIR) are widely used as instrument of spectral analysis and substance identification in the air and on surfaces [1–3]. Dynamic type Fourier transform spectrometers despite of its ideological simplicity have a number of complex structural elements, in particular, they include the movable mirror assembly with a strictly straightforward motion and accurate orientation of mirrors in space to within a few seconds. Additional complexity is the task of creating a control system for a linear motor. A separate charge element is the reference laser channel (separate or combined with the main interferometer and single-mode He / Ne-laser as a reference source), greatly affecting the structural and operational characteristics of the Fourier transform spectrometers [1]. These essential elements are characterized by the implementation of the classical scheme of the Michelson interferometer. It should be noted that there is a design, the most widely used in land-based mobile complex FTIR in space-based equipment, where the linear movement of mirrors replaced by an oscillating pendulum suspension [1, 4–6].

In recent years, foreign literature works appeared describing the basic construction Fourier transform spectroradiometer using the optical circuit with a rotating plane-parallel plate (see Figure 1). The presented results [7, 8] draw attention to the spectrometer because of the high frequency scanning, sufficient spectral resolution, but the main advantage – a technically simple scanning system.

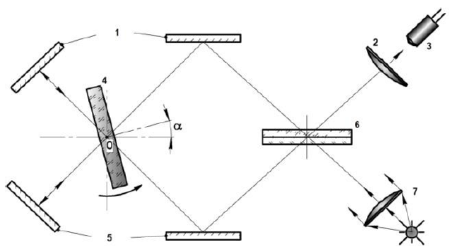

Figure 1. Scheme of interferometer with rotating plate. 1, 5 – mirrors (R100%); 2 – collecting lens; 3 – photodetector; 4 – rotating plate; 6 – beamsplitter / compensator; 7 – radiation source.

Numerical Computation

In [9] it is obtained dependencies of the rays optical path difference in the interferometer according from rotation angle of the plate, designed for multiple versions of optical materials. Figure 2 shows these dependencies for the wavelength λ = 10 μm for the four most common materials of infrared (IR) optics.

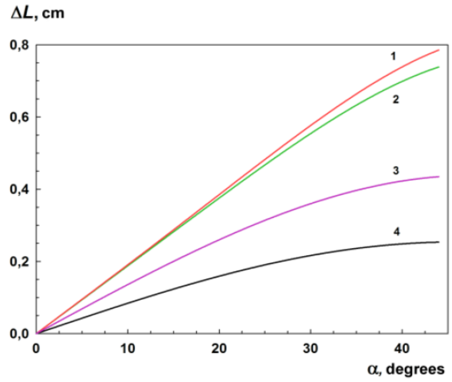

Figure 2. The dependence of optical path difference for λ = 10 μm in the interferometer for various optical materials from the rotation angle of the plate with thickness 10 mm. 1 – KCL; 2 – KBr; 3 – ZnSe; 4 – Ge.

In the range from –20° ... +20° with absolute linearity error of less than 2 microns, which is better than λ / 4 at the relative accuracy of 0.056%, showed dependence in Figure 2 can be represented as a linear plots. In this rotation angle of the plate range the optical path difference (OPD) with a high accuracy can be determined by rotation angle of the plate. This simplifies and facilitates the construction of a Fourier transform spectrometer, because a reference laser channel in that situation is not needed. The use of encoders with an output signal in the form of a Gray code allows to determine the rotation angle of the plate, which will enable to determine rays OPD in the interferometer without using the laser reference channel.

Figure 2 shows that the greatest OPD between presented submissions is attainable for KCl, KBr. In this case, for a specified operating range of angles achievable spectral resolution of no worse than $\Delta\nu = 1/\Delta L = 3$ cm^{-1}, which is a working value for the FTIR for remote sensing systems. However, it should be noted that despite of the high spectral resolution obtained on the plate, manufactured by KBr, use of this material, due to the high hygroscopicity [10], assumes the sealed box with a dehumidifier for the interferometer. This is limiting fact in non-laboratory conditions, so in this paper we propose to consider the following non-hygroscopic materials – Ge and ZnSe.

For a angles range ° –20 ... + 20 ° using a germanium optics allow to obtain the maximum path length difference ΔL = 0,17 cm, which is equivalent to the spectral resolution about 6 cm^{-1}. Interferometer with such spectral resolution can be applied for the development of remote monitoring systems, equipped with uncooled photodetectors which working spectral resolution is in order of 8 cm^{-1}. The main design characteristics of the interferometer with rotating plate discussed in detail in [7].

The proposed concept of the interferometer is perspective for a creation of spectroradiometric systems in average spectral resolution. The transition from the linear displacement of the movable mirror, which is typical for a Michelson interferometer, to the rotation of the plate simplifies the design of the interferometer optomechanical unit and a control system, reduces the weight and size and improves performance.

In paper the optical system and parameters of germanium doublet lens is calculated using a software package ZEMAX. Application of a doublet lens is due to the requirement to minimize the loss of incoming light reflection. During optimization of the lens spherical aberration are controlled. That gives the greatest working divergence range of the rays in the interferometer which value is 4,5° to the specified size of photodetector.

Further optimization of the lens is carried out by improving the parameter collection efficiency energy at the photodetector depending on the size of the illumination spot.

The numerical calculation of the interferometer parameters is held in conjunction with the collective lens by software system ZEMAX. Optical elements material (collecting lens and splitter / compensator) – Ge. ZnSe as a material of the rotating plate allows greater OPD at the same rotation angles of the plate compared with Ge, and thus improves the spectral resolution.

Rejection of the reference laser channel simplifies the design of the Fourier transform spectrometer, but the non-linearity in the OPD depending on the rotation angle of the plate can introduce distortions in the restored spectra. Figure 3 shows the absolute error of the rays OPD in the interferometer according to the rotation angle. For further calculations as the material of the rotary plate will consider ZnSe.

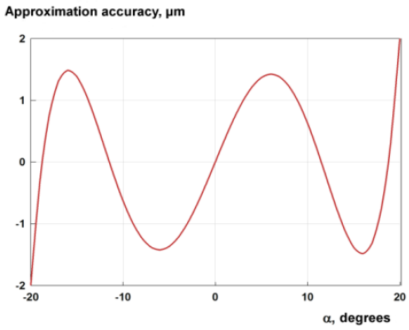

Figure 3. Optical path difference rejection from the linear dependence of rotation angle for a ZnSe plate and wavelength λ = 10 μm.

As shown on Figure 3 the excess of the rotation angle range of the plate on ± 5° dependence of the OPD ΔL from the rotation angle α of the plate becomes substantially nonlinear. Restricting the operating range of the rotation angle of the plate to the range ± 5° achieves spectral resolution is no better than 12 cm^{-1} for the path difference of 0,08 cm, that's not enough for chemical analysis of small molecules such as ammonia, so the use of FTIR with such permission will be significantly limited in practice.

As can be seen from Figure 4a for small angles given rectangular apodization retardation deviation from a linear dependence on the rotation angle of the plate does not introduce significant distortion in the restored spectrum, due to the linear nature of the deviation. So for limiting the deflection angles of the plate α = ± 5° quadratic correlation coefficient of calculated instrumental functions with the phase errors and the ideal is R^2 = 0,911; for α = ± 10° – R^2 = 0,921; for α = ± 15° – R^2 = 0,872 and α = ± 20° – R^2 = 0,667. Thus, for a 10 mm ZnSe plate a limit of the spectral resolution about 6 cm^{-1} can be expected for a range of angles of ±15° with a quality of instrumental function $R^2 \geq 0{,}9$.

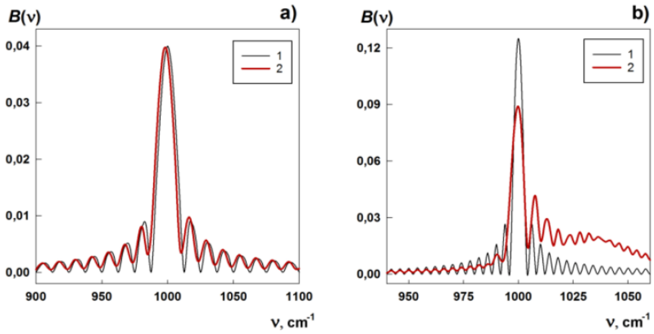

Figure 4. Distortions in the restored spectrum. Curve 1 corresponds to the instrumental function of the perfect interferogram, 2 – interferogram with phase errors. Figure 4 (a) shows the instrumental function for rotation angle of the plate ± 5° (spectral resolution 12.5 cm^{-1}); Figure 4 (b) – for the rotation angle of the plate ± 20° (spectral resolution of 4.0 cm^{-1}).

However, the calculated spectral resolution is not always enough for the spectral analysis of low molecular weight compounds (eg, NH_3), therefore it is necessary to increase the rotation angle range of the plate, which will increase the spectral resolution. From Figure 4b can be seen that for large values of the rotation angle of the non-linearity in the accuracy of determining the optical path difference leads to significant distortion of the shape of the spectral line, which can be a fundamental difficulty in conducting spectral analysis of low molecular weight substances with narrow spectral lines.

To eliminate the distortions of the spectral lines may be used a method of digital filtering, in which the restoration of the spectrum produced by the convolution of interferogram and apodization function [1, 11]. The use of apodization functions in the restored spectra can suppress secondary maxima, thus reducing the distortion introduced in the spectrum. For numerical assessments of the effectiveness of such a filter function used in the form of apodization Happ-Genzel and Blackman-Harris. The results of calculations of the spectra for the rotation angle of the interferometer plate ± 20° are shown in Figure 5.

The application of apodization in the reduction of the spectra leads to a broadening of the spectral lines, and thus to the deterioration of the spectral resolution which is a pay for improved forms of renewable spectra. Analysis of the line width at its half height for all three lines shown in Figure 5 shows that the use of apodization lead to a significant broadening of the instrumental function about 1,5 times. Thus, the use of digital filtering in form of interferograms convolution with apodization function will significantly reduce the distortion of the identified instrumental functions and, consequently, of narrow spectral lines. For a working angles range $\alpha = \pm 20°$ and apodization function Blackman-Harris attainable spectral resolution of 6 cm^{-1} with the satisfactory quality of instrumental function, Happ-Genzel calculation gives a value of 5 cm^{-1} at a somewhat lower quality of instrumental functions.

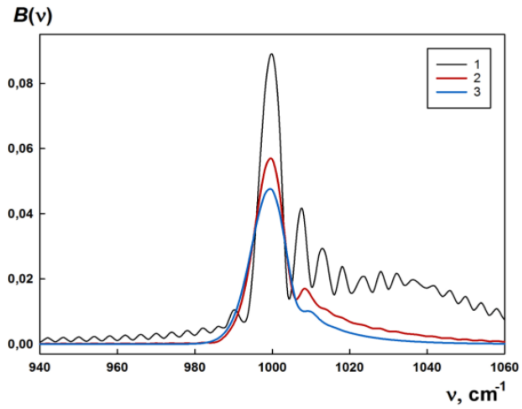

Figure 5. Monochromatic source spectrum ($\nu_0 = 1000$ cm^{-1}) which interferogram includes phase errors and corresponds to the rotation angle of the plate by 20 °. Curve 1 – rectangular apodization, 2 – Happ- Genzel apodization, 3 – Blackman-Harris apodization.

Summary

For given characteristics of the interferometer optimized version of the collecting lens for the photodetector is proposed and the basic elements of the interferometer are calculated. The Ge as a material of IR optics is considered. It makes possible to apply the proposed scheme for nonlaboratory analysis problems for the rotating plate – ZnSe.

Practical implementation of the proposed scheme of an interferometer with rotating plate allows to eliminate the need to use the reference laser channel, which should increase the stability of the interferometer, reduce the size and increase reliability. The deviation from linearity according to the difference in the optical path of the rays in the interferometer by a rotation angle of the plate makes a significant distortion in the shape of the spectral lines of the rotation angles greater than ± 15° from the zero point of the optical path difference. A spectra filtration in form of a convolution recorded interferogram with apodization function as Happ-Genzel and Blackman-Harris is proposed. It is shown that the use of such filtering allows eliminating the distortion, but it lowers by 1.5 times the spectral resolution.

Practical implementation of the interferometer is discussed. The implementation of digital filtering restored spectra will allow obtaining a spectrum with a resolution of better than 6 cm^{-1}, which will conduct a spectral analysis of a wide range of substances in the infrared region. The qualitative type of the instrumental function for the proposed interferometer is obtained by mathematical modeling.

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