Multichannel IR Fourier transform spectrometer

I Sh Khasanov ¹, V A Vagin¹ and Il S Golyak²

¹Scientific and Technological Center of Unique Instrumentation of the Russian Academy of Sciences, Moscow, 117342, Russia
²Bauman Moscow State Technical University, Moscow, 105005, Russia

Abstract. The authors propose to implement a multi-channel continuous scan Fourier spectrometer for simultaneous recording and analysis of the spectral characteristics of several objects. To implement such a scheme is used multiprobe fiber in which several optical fibers, at one end, are connected in one optical connector and fixed in the output of interferometer. In this scheme, the Fourier spectrometer is used as a modulator. On the other hand, each fiber individually mated with the test sample and its own radiation detector. The spectral resolution of the proposed system is 1 cm⁻¹. For the system the aperture of the spectrometer from the condition of minimum spectral resolution and optical fibers parameters is calculated. Using the proposed scheme emission spectra of helium neon lamp have been registered for each single fiber with diameter of 1 mm and a numerical aperture NA= 0.22.

1. Introduction

To solve some of modern scientific, scientific-technical and production tasks, sometimes it becomes necessary to simultaneously measure the spectral characteristics of an object of research by various spectral methods and in different spectral regions. In this paper we propose and examine the physical possibility of organizing such measurements using a single spectrometer.

The effectiveness of modern production is determined not only by the emergence of new production technologies and the introduction of new high-tech tools, but also by the quality of continuous (rapid) monitoring of the various stages of the production process, with the ability to react quickly to its change (i.e., active management of these processes). To ensure this, it is necessary to effectively measure the parameters (characteristics) of the process at its key stages. Since the measurement of the chemical composition of the input, intermediate and final product is the most important condition in many technological processes (in the food, chemical, oil refining, pharmaceutical and other industries), development of a system for diagnostics and control over complex chemical processes providing such a measurement is extremely topical. One of the most effective means of measuring various characteristics of the objects under study is spectral instruments.

Spectral methods make it possible to perform a spectral analysis of the sample under study and determine the presence of a substance from the optical absorption lines and then, by measuring the optical density at these lines, to measure the concentration of the desired substance in the sample. In this case, the measurement can be made both in the sample taken and with the help of special devices (for example, optical fiber probes) directly inside the process.

The use of fiber-optic probes matched with spectral instruments allows carrying out various spectral measurements in remote, hard-to-reach and dangerous places without the need for sample preparation. Fiber-optic probes were used in the first place in conventional spectrometers [1], as one of the...
improvement. But in the future specialized spectrometers were created, oriented only to fiber-optic probes [2, 3, 4].

An important task was the creation of spectrometers, which could work directly with several probes and carry out measurements on each channel. In this case, one device allows to control several phases of the technological, physical or chemical process. For such measurements, the MATRIX-F Fourier spectrometer (Bruker, Germany) was developed. This spectrometer uses a 6-channel multiplexer for the possible simultaneous connection of 6 probes. It allows the use of one instrument for sequential process control in 6 reactors. The original optical-mechanical system provides the necessary switching of the spectrometer from one probe to another and allows sequential spectral measurements at 6 points of the process under study.

Thus, the actual task is the development of a continuous scanning spectrometer, which would allow simultaneous measurements at several points in the technological process and obtain measurements in real time.

2. Scheme for simultaneous registration of a signal from several samples

We propose a scheme of an IR Fourier spectrometer for continuous scanning, which will allow simultaneous measurements of the investigated object with several probes at different points [5]. To implement such a scheme, several optical fibers on one side are combined into one optical bundle (figure 1) and fixed in the corresponding fiber optical connector at the output of the interferometer.

Using an optical condenser installed at the output of the Fourier spectrometer, the radiation emitted by the interferometer is applied to each optical fiber. Thus, the proposed Fourier spectrometer becomes a multichannel instrument. Each individual probe, through the appropriate fiber, monitors its object through its receiver (figure 2). As a result, it is possible to simultaneously measure several objects or different stages of a certain process, for example, in a production line.
In such a scheme, the radiation source is placed at the input of the interferometer. With the aid of a special optical system (for example, an off-axis mirror paraboloid) in the focus of which the radiation source is located, a collimated flux of light is directed to the input of the interferometer. An interferometer with continuously variable optical path difference acts as an optical modulator of radiation, creating an initial interferogram. Then the interfering radiation is directed to the optical connector, to which is connected an optical fiber bundle consisting of several separate optical probes. Each probe ends with its IR receiver. Thus, it is possible to perform sequential or simultaneous recording of interferograms from each individual receiver.

3. Estimating the luminosity of the proposed scheme of the Fourier transform spectrometer

With such a system of operation, it is necessary to calculate the Fourier transform spectrometer’s luminosity, depending on the characteristics and number of probes. The Fourier transform spectrometer is a high-speed instrument, its luminosity is determined by the value of $\Omega S$, where $S$ is the effective cross section of the light flux incident on the beamsplitter, calculated by the formula:

$$S = \pi D^2 / 4,$$

(1)

where $D$ is the effective beam splitter diameter, and $\Omega$ is the solid angle, which determines the beam divergence of this light flux. For small $\alpha$, the solid angle is given by:

$$\Omega = \pi \alpha^2,$$

(2)

where $\alpha$ is the maximum deviation angle from the radiation axis. It is known [6] that the requirement for the beam divergence of the above-mentioned light flux is determined by the maximum spectral resolving power ($R$), which one wants to obtain on the Fourier transform spectrometer, namely

$$\Omega R \leq 2\pi.$$

(3)

In the case under consideration, the element limiting the luminosity of the spectral system is optical fiber. The diameter of the optical fiber ($d$) usually does not exceed 1 mm. All the radiation emitted from the optical fiber is concentrated near its axis in the angular range ($\varphi$) of approximately $\pm 15^\circ$. Thus, the Lagrange-Helmholtz invariant leads to the relation

$$\varphi d = D \alpha.$$

(4)

From (2) and (3) it follows

$$\alpha^2 \pi R \leq 2\pi$$

(5)

or

$$\alpha \leq (2 / R)^{1/2}.$$

(6)

Thus, a Fourier transform spectrometer with an effective beamsplitter diameter is sufficient to work with such an optical fiber

$$D = \varphi d / \alpha = \varphi d / (2 / R)^{1/2}.$$

(7)

With a spectral resolution of the order of 1 cm$^{-1}$, realized in the proposed Fourier spectrometer with a short-wave boundary of the spectral range of 5000 cm$^{-1}$, we will have $R = 5000$.

Substituting the values of the resolving force $R$, the diameter $d$, and the fiber aperture into the resulting equation (7), the effective beam splitter diameter will be $D = 12.5$ mm.

With a spectral resolution of 4 cm$^{-1}$, the diameter of the beam splitter is $D = 6$ mm.

It can be seen from the calculations that the interferometer required for fiber-optic measurements can be small, with a beam splitter diameter (and corresponding dimensions of other optical elements of the interferometer and matching optics) not exceeding 10-20 mm. On its basis, a portable, portable Fourier spectrometer or a spectral system of input, intermediate and output monitoring of technological lines can be created.

In the case of working with several probes, it is not necessary to increase the size of the beam splitter. It will be necessary to increase the light size of the radiation source in order to illuminate the entire input area of the fiber optic harness at the output of the interferometer. Accordingly, each fiber will have a part of the radiation satisfying the relation (4).
The multi-probe IR Fourier transform spectrometer will differ significantly from the multi-probe NIR Fourier transform spectrometer due to the materials of the optical fibers used and to the spectral sensitivity of the photodetectors. In the near IR range are used quartz optical fibers [7]. Optical absorption in them is much smaller than in polycrystalline and chalcogenide optical fibers used in the middle IR range. Accordingly, the multi-probe Fourier spectrometer of the near-IR range can use significantly longer probes (up to 10 meters or more), which is especially important for working with the objects that are remote from the spectrometer.

4. Experimental proof of work of a breadboard model
To study the possibilities of working in multi-channel mode with several probes, preliminary measurements were made on the model of the Fourier spectrometer of the visible and near IR bands (figure 3). The spectral resolution of the spectrometer is 1 cm$^{-1}$, which is ensured by using corner reflectors (tetrahedra) instead of flat mirrors. Such a design allows to reduce the requirements for the stability of their spatial position, since the incident beam is reflected from them strictly parallel to the original one [8].

![Figure 3. Fourier transform spectrometer breadboard model.](image)

The input of the Fourier spectrometer was illuminated by the emission of a gas-discharge neon lamp. The radiation emitted from the interferometer was focused at the input of a shortened version of the fiber probe-a bundle (figure 4) consisting of three optical fibers of a larger cross-section with a core diameter of the order of 0.6-1.0 mm (fiber type OKK800 / 880 / 1200T with a numerical aperture NA = 0.22).

![Figure 4. Fiber harness for adjusting and calibrating a multi-probe Fourier transform spectrometer for the visible and near-IR bands.](image)

Then, successively, each optical fiber was connected to a photodetector and the spectrum of radiation transmitted through this optical fiber was recorded. Thus, the variant of operation in the multichannel mode was simulated. In figure 5 shows the spectra obtained on the optical fiber 1 (a) and optical fiber 2 (b).
As you can see, this is one and the same spectrum, differing in intensity and in reference to wave numbers. The first is due to the fact that the inputs of fiber optic cables are not equally illuminated, and also due to the difference in their optical characteristics. The relative shift in wave numbers is due to the fact that the optical axes of light beams coming from the interferometer to the inputs of fiber-optic probes (cables) are not parallel to each other, but turn out to be at a small angle. Accordingly, these axes and with respect to the optical axis of the laser radiation in the reference channel turn out to be at various random (very small) angles. This leads, when processing interferograms, to a relative frequency shift.

In figure 6 shows the emission spectrum of an individual line of a gas-discharge neon lamp for two different fibers.

Figure 5. A fragment of the emission spectrum of a gas-discharge neon lamp (fiber 1 (a), fiber 2 (b)).

Figure 6. The emission spectrum of a separate line of a gas-discharge neon lamp (fiber 1(a), 2 (b)).
Indeed, if the axis of the light beam is inclined at an angle $\alpha$ to the optical axis of the interferometer, then when the moving mirror moves at a distance $d$, the optical path difference ($\delta$) for the above ray will change according to the law $\delta = 2d \cos \alpha$, which explains the above frequency shifts in obtained spectra [9].

Thus, when working in a multi-probe variant, each fiber channel must be pre-calibrated in intensity, if necessary and, most importantly, in frequency (wave numbers).

**Conclusion**

A wide variety of commercially available optical-mechanical and electronic components makes it possible to create a portable IR Fourier spectrometer operating simultaneously with several fiber-optic probes. Due to the use of probes of various designs, effective radiation and reception of the light flux are performed for a variety of spectroscopic applications. Further research should be aimed at creating a multi-probe Fourier spectrometer and on its basis an integrated, multifunctional and highly optimized system that solves the problems of spectral analytics of technological processes.

**Acknowledgments**

The proposed spectrometer was developed and manufactured at the "Scientific and Technological Center of Unique Instrumentation" of the Russian Academy of Sciences (STC UI RAS). The work was carried out within the framework of the state budgetary work 40.4 (Fundamental research program of the State Academies of Sciences "Investigation of the possibilities of creating a specialized Fourier transform IR spectrometer with a fiber-optic probe system for on-line molecular spectroscopy").

**References**

[1] Balashov A A, Vagin V A, Viskovatykh A V, Zhizhin G N, Pustovoit V I and Khorokhorin A I An AF-1 analytical Fourier-transform spectrometer for a wide field of applications 2003 *Instruments and Experimental Techniques* 46 (2) 219-221

[2] Balashov A A, Vagin V A, Moshkin B E, Khitrov O V and Khorokhorin A I Fiber-optic Fourier-Spectrometer 2009 *Instruments and Experimental Techniques* (6) 143

[3] Balashov A A, Vagin V A and Khorokhorin A 2016 *Instruments and Experimental Techniques* № 1 158. DOI: 10.7868/S0032816216010304

[4] Danielyan G L, Bazhanov Yu V, Savosin S V and Markov S N Development of a wide-range sensor - a mini-spectrometer with fiber input for spectral analysis of biological structures and liquids 2007 *Optical J* 74 (12) 55-61

[5] Balashov A A, Vagin V A, Viskovatykh A V, Zhizhin G N, Pustovoit V I and Khorokhorin A I Multichannel dynamic IR Fourier-spectrometer 2017 *J. of Appl. Spectroscopy* 84 (4) DOI: 10.1007/s10812-017-0526-z

[6] Morozov A N and Svetlichnyi S I *Fundamentals of Fourier Spectroradiometry* 2014 (Moscow: Nauka) 456 p. [in Russian]

[7] Burkov V D and Ivanov G A *Physico-Technological Fundamentals of Fiber-Optic Technology* 2007 (Moscow: MGUL) 222 p. [in Russian]

[8] Griffiths P R, Haseth J A De and Winefordner J D *Fourier Transform Infrared Spectrometry*. 2007 2nd ed. (Wiley) 560 p.

[9] Morozov A N, Svetlichnyi S I and Fufurin I S 2015 Reports of the academy of sciences 464 (2) 156-159 DOI: 10.7868/S0869565215260114