Static Fourier-transform spectrometer with spherical reflectors

Gao Zhan

A compact reflection Fourier-transform spectrometer without moving parts is developed. The spectrometer consists of two spherical reflectors: a Sagnac interferometer and a linear detector. The developed system is as small as 202 mm long × 185 mm wide × 100 mm high. The optics and the system configuration are described, and the preliminary experimental results are shown. © 2002 Optical Society of America

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1. Introduction

Fourier-transform spectroscopy is a powerful measurement technique because of its throughput advantage.[1,2] The principle is based on the two-beam interference phenomenon, and the spectrum is reproduced by a discrete Fourier transform of the interferogram. Such an interferogram can be formed either in the temporal domain or in the spatial domain, according to the chosen interferometer.[3]

The spectrometer based on the Michelson interferometer, which acquires an interferogram in the temporal domain, is referred to as the conventional Fourier-transform spectrometer. However, high accuracy of the mechanical mirror drive and high flatness of the interferometer's beam splitter and mirrors make the Fourier-transform spectrometers expensive and complex, especially in the ultraviolet and visible ranges. These drawbacks motivate the development of the static, namely, no-moving-parts, Fourier-transform (StFT) spectrometer. Most are based on the Sagnac interferometer or a birefringent crystal, for example, a Savart plate or a Wollaston prism. Several configurations have been proposed.[4–7]

My purpose in this paper is to present a simple and no-moving-parts spectrometer that I and my colleagues designed and call the static reflection Fourier-transform spectrometer (SRFTS), which is based on a Sagnac interferometer with two identical spherical reflectors. This configuration is different from the other static spectrometers that are based on the Sagnac interferometer with a Fourier lens. In the SFRTS, the optical path is folded, so the instrument becomes compact. Furthermore, it can also work in a wider wave band as long as the beam splitter is not the limiting factor for the spectral range.

2. Principle

The concept of the SRFTS is shown in Fig. 1. It consists of only two identical spherical reflectors, two identical plane mirrors, a beam splitter, and a linear CCD. The focal point of spherical reflector 1 is inside the Sagnac interferometer and coincides with the focal point of spherical reflector 2. Mirrors 1 and 2 are at angles of 30° and 150° with the beam splitter, respectively. The beam from the source is reflected and focused by spherical reflector 1 and then is converged to the beam splitter. The laterally sheared beams with the Sagnac interferometer are reflected by spherical reflector 2. The interferogram is detected with a linear CCD. Figure 2 shows the schematic optical layout that is equivalent to the one in Fig. 1. The path difference Δ between two components is given by[8]

$$\Delta \approx dx/f, \tag{1}$$

where f is the focal length of the spherical reflector, x is the spatial coordinate on the detector plane, and d is the distance between the corresponding two points of the two virtual images. The shearing distance d is given by

$$d = 2t, \tag{2}$$

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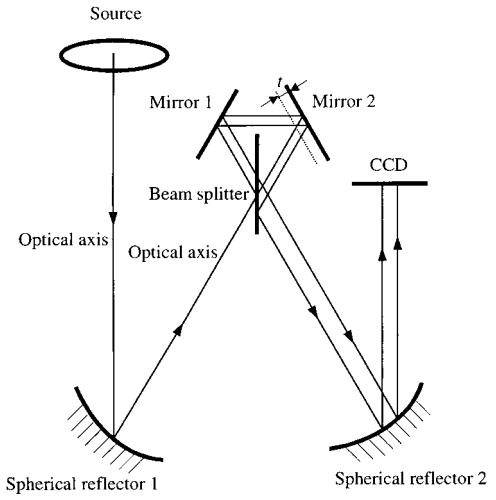

Fig. 1. Optical layout of the SRFTS.

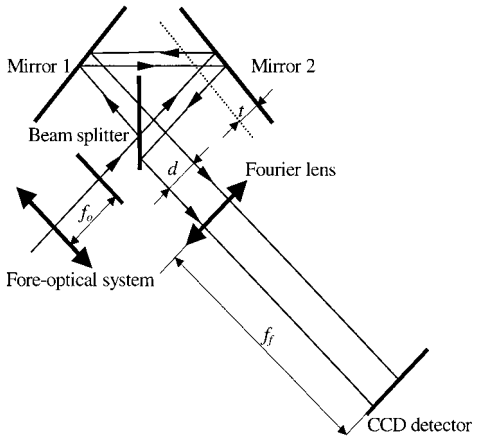

Fig. 3. Optical layout of the SFT spectrometer based on the Sagnac interferometer.

where t is the distance between mirror 2 and the mirror image of mirror 1 with respect to the beam splitter.

Figure 3 shows the configuration of the StFT spectrometer based on the Sagnac interferometer described above. The incident light is divided into two and forms virtual images on the front focal plane of the Fourier lens, which is also the back focal plane of the fore-optical system. The interferogram formed by the two virtual images is recorded with a CCD detector. Compared with this instrument, the SRFTS has two advantages. First, the instrument becomes compact because the optical path of the SRFTS is folded by spherical reflectors 1 and 2. Second, the instrument is easy to work in a wide wave band because all optical elements except the beam splitter are reflectors. The modulation depth V of the two-beam interferometer is given by[9]

$$V = \frac{2E_1E_2}{E_1^{\,2} + E_2^{\,2}}, \tag{3}$$

where E_1 and E_2 are the amplitudes of the two beams, respectively. In the SRFTS, one beam is reflected twice and the other is transmitted twice. Thus one has

$$V = \frac{2RT}{R^2 + T^2}, \tag{4}$$

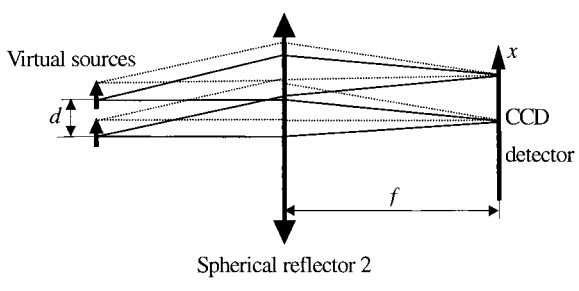

Fig. 2. Schematic optical layout equivalent to Fig. 1.

where R and T are the reflectance and the transmittance of the beam splitter, respectively. Hence the modulation depth of the interferogram is affected by the ratio of the reflectance and the transmittance of the beam splitter. The modulation depth of the interferogram becomes 1 when the ratio is equal to one. But in practice, it is difficult to make a beam-splitter coating that maintains a close match between reflectance and transmittance over a wide spectral range. For example, in case of $R{:}T = 2{:}3$, the modulation of the interferogram becomes 92%. For this reason, the second feature is achieved if the beam splitter is not the limiting factor for the spectral range. It should be noted that the SRFTS also has the same advantage as the StFT Sagnac interferometer in that the visibility of the interference fringe is independent of the light source size because the interference fringe produced on the detector plane is equivalent to the one of equal inclination.

Some authors also used the reflective optics in the design of the StFT spectrometer (see, for example, Ref. 10 in which a toroidal mirror is used but the

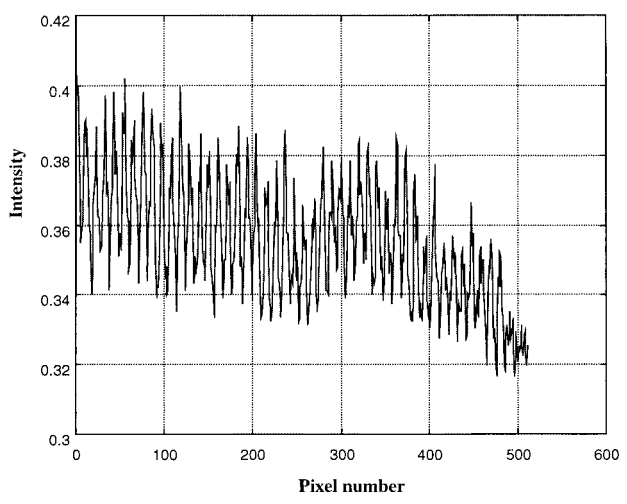

Fig. 4. Interferogram of a He–Ne laser.

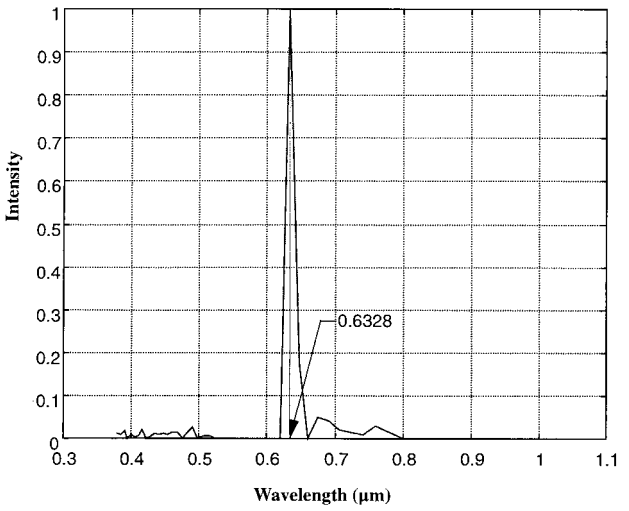

Fig. 5. Reconstructed spectrum of the He–Ne laser.

mirror is obviously expensive and its production is complex).

3. Experiment and Results

The focal length and the diameter of spherical reflector 1 are 160 and 20 mm, respectively. Spherical reflector 2 is the same as spherical reflector 1. The shift distance t in the SRFTS is 0.95 mm, and the shearing distance d is 1.9 mm. The CCD that was used in this study has 512 pixels with a pixel size of 10 μm, and the spectral range of this detector covers 0.38–1.1 μm. The maximum path difference between the two beams at the end of the detector corresponds to 0.030 mm. Hence the resolution of this spectrometer is 329 cm^{-1}. Several experiments were carried out, and the results demonstrated the feasibility of the system. Figure 4 shows the interferogram of the He–Ne laser source, where a triangle function is applied as an apodization filter. Figure 5 shows the reconstructed spectrum of a He–Ne laser. The peak wavelength corresponds to 632.8 nm. Figure 6 shows the interferogram of a tungsten lamp,

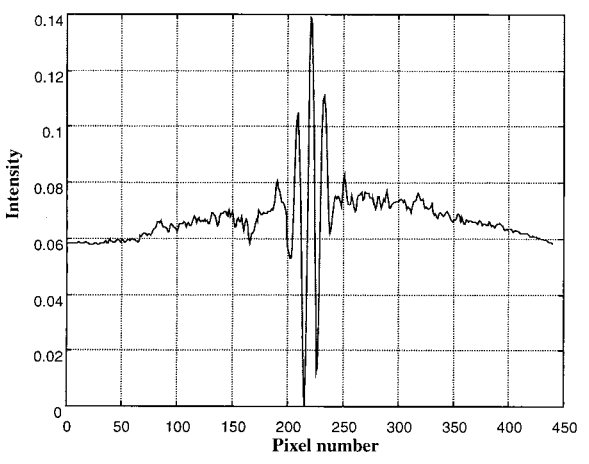

Fig. 6. Interferogram of a tungsten wire source.

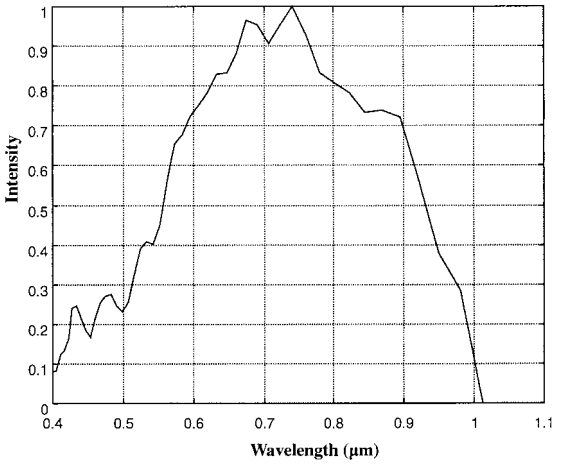

Fig. 7. Reconstructed spectrum of the tungsten wire source.

and Fig. 7 shows its reconstructed spectrum. A triangular function is used as an apodization filter in the Fourier transformation.

4. Discussion

I and my colleagues have developed a new StFT spectrometer in a compact size and have proven the feasibility of the system by computing the spectra of well-known light sources. The main advantages of the system are compactness, simplicity, and the absence of moving parts. The instrument can be used in wide wave band if the beam splitter is not the limiting factor for the spectral range. Furthermore, this spectrometer also has the advantage that the visibility of the interference fringe is independent of the light source size. These features make the system well applicable to field use, gas analysis, on-line measurement, and in-process monitoring.

To improve the spectral resolution of the system, it is necessary to use a CCD sensor with a great number of pixels. The path difference also can be enlarged either by a widening of the separation t in the Sagnac interferometer or by use of a spherical reflector with a shorter focal length. The signal-to-noise ratio can be improved, and the stray light can be reduced further by careful adjustment of the optical system.

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