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Design of a novel low-background spectrometer for infrared sensitive detection

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Abstract: The design of a novel low-background spectrometer based on lamellar grating interferometer (LGI) is presented. Reducing background noise helps to improve the spectrometer system detectivity for detectors operating under background limited performance (BLIP) regime, and then improve the signal to noise ratio (SNR) of spectrometer. The principle is that perfect mirrors do not emit blackbody radiation since their emissivity equals zero. Therefore, a lamellar grating interferometer based on a "cold" source and a "cold" detector becomes an extremely sensitive instrument because of the reduction of background radiation. Theoretical analysis shows that the system detectivity can be improved substantially with background radiation dropping. In ideal case, for a typical HgCdTe detector, the real BLIP detectivity obtained and corresponding SNR can be improved by three orders of magnitudes when background radiation is reduced from 300 K to 77 K. Besides, without cooling the interferometer, this configuration is more compact and easier-to-build compared with previously reported low-background Michelson spectrometer. This design has important significance for infrared sensitive detection.

Key words: emissivity, background radiation, lamellar grating interferometer, detectivity, SNR
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一种新型的用于红外灵敏探测的低背景光谱仪

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摘要:提出了一种新型的基于反射光栅干涉仪的低背景光谱仪,当使用工作在背景限制条件下的探测器时,降低背景噪声,有利于提高光谱仪系统的探测率,进而可提高光谱仪的信噪比.由于理想反射镜发射率为零,故其干涉仪组件无黑体辐射.因此,基于低温光源、低温探测器和光栅干涉仪的光谱仪,其探测到的背景辐射大幅降低.进而得到低背景下的探测率实现灵敏探测.理论分析表明随背景辐射的降低,背景限制条件下探测器的探测率可大幅提高.理想情况下,对工作在背景限制下的碲镉汞探测器,当由 300 K 的背景辐射降至 77 K 时,其探测率和相应光谱仪的信噪比可提高三个数量级.另外,与之前报导的低温迈克尔逊光谱仪相比,它结构紧凑且无需对干涉仪降温,易于搭建.该设计对红外灵敏探测有重要意义.

关 键 词:发射率;背景辐射;光栅干涉仪;探测率;信噪比

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Introduction

Fourier transform spectroscopy (FTS) has evolved into a powerful and widely used research technique in both laboratory and industry. However, in some applications, e.g., quantum information, atmospheric optics and molecular dynamics, weak infrared signal calls for highly sensitive detection. For an optimally designed spectrometer, the detectivity of a detector is defined as the normalized signal to noise performance, which determines the limit of weak signal detection[1], and it is lim-

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ited by two factors, device noise and background noise. To suppress device noise, cryogenic instruments are usually employed to cool the detector. Practically, it is always desirable to operate a detector under background limited performance (BLIP) for optimal detectivity[2-3]. In such a case, background noise, other than the device noise, is dominant to decide the detection capability. An effective way to obtain higher BLIP detectivity of the system is to reduce background noise via building a low-background system.

Usually, there are two kinds of two-beam interferometers used in Fourier transform infrared spectroscopy (FTIR), the conventional Michelson interferometer and the compact lamellar grating interferometer (LGI)[4]. The schematic of a Michelson FTIR is shown in Fig. 1 which is composed of a Michelson interferometer, an infrared source, a detector and guiding lenses. The interferometer consists of a beamsplitter and two reference mirrors (fixed mirror and movable mirror). Using beamsplitter, radiation is divided into two parts and then recombined after an optical path difference introduced. For sensitive detection, McDonald *et. al* developed the first low-background Michelson FTIR by placing the interferometer, detector and source in cryogenic shields[5]. Although the signal to noise ratio (SNR) of such spectrometer can be improved obviously, the disadvantages of bulky and expensive greatly restrict its widespread application until now. For a LGI, the main feature is a movable binary grating, which acts as both beamsplitter and components causing differential delay in Michelson interferometer. It was first demonstrated experimentally by Strong and Vanasse in 1960[6], and became more practical after the advancements in micro-fabrication and micro-electro-mechanical system (MEMS) technologies, which enables the fabrication of precise diffraction gratings and feasible actuations[7-8]. This instrument is compact and robust. With comparable performance to Michelson type, lamellar grating spectrometers have been developed in visible, infrared and terahertz region[9-12]. However, LGI spectrometer introduced to achieve sensitive detection has not been reported up to now. In this paper, a novel low-background LGI spectrometer design is proposed.

The paper is organized in the following structure. First, we provide a simple analysis to prove that a low background can improve the sensitivity of a spectrometer and point out possible directions to reduce the background. Sources of background radiation in FTIR are discussed as well. In Sect. 2, the low-background LGI spectrometer scheme is proposed. Both the configuration design and operation principle are presented in detail. Also, a comparison between the conventional spectrometer and our design is given. In Sect. 3, theoretical calculated BLIP detectivity of photoconductive HgCdTe detectors is presented to discuss the performance of our design.

1 Analysis

Signal to noise ratio of a spectrometer system is the key parameter to represent the sensitivity, which is determined by the comparison of signal and noise. Generally

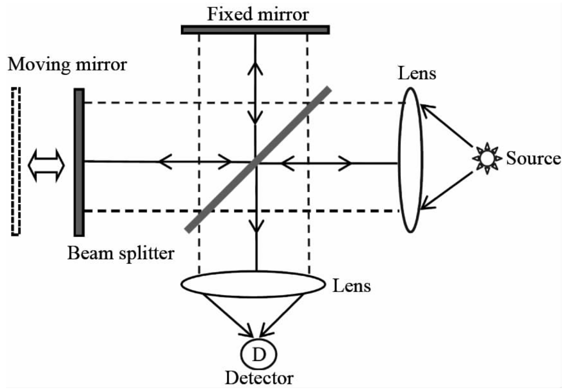

Fig. 1 Schematic representation of a conventional Michelson FTIR
图 1 传统迈克尔逊傅利叶红外光谱仪示意图

speaking, the noise of a spectrometer mainly includes detector noise, digitization noise, sampling noise, folding noise, vibrations and microphonics noise[1]. For an optimally designed spectrometer, each instrument should be designed well enough so that detector noise is dominant compared with noise from all other sources combined. In such a case, the SNR of a two-beam spectrometer can be calculated by the following expression[1]:

$$SNR = \frac{U_\sigma \Theta \Delta\sigma t^{1/2} D^* \xi}{A_d^{1/2}} \quad , \quad (1)$$

where U_σ is the spectral energy density of a signal source at wavenumber σ. $\triangle\sigma$ is the resolution, Θ is the optical throughput, t is the measurement time, D^* is the detector specific detectivity, ξ is the efficiency of the interferometer and A_d is the detection area. Considering a given FTIR with fixed optimal $\triangle\sigma$, measurement time t, and U_σ, Θ, ξ are physical constants, then the SNR is determined only by detectivity: $SNR \propto D^*$. Detectivity is generally given as[13]:

$$D^* = \frac{R\sqrt{A_d \cdot \Delta f}}{i_n} \quad , \quad (2)$$

where R is the spectral current responsivity, $\triangle f$ is the frequency band width and i_n is the total noise current. According to the origins, noise of a photodetector is normally categorized into device noise, background noise and signal noise. The device noise is induced by dark current of the detector, which is closely dependent on the device temperature. The background noise and signal noise are produced by the background radiation and incident signal radiation, respectively. These three sources of noise compete with each other and one of them dominants depending on different operation condition. In general, device noise is suppressed effectively and the detectivity can be improved substantially when the detector is cooled. However, the detectivity will be saturated once the operation temperature is lower than the BLIP temperature. In such a case, the only choice to get higher detectivity is to decrease the background noise.

As we know, when placing a detector at room temperature, the detectivity is affected by radiation emitted from its surrounding objects. The amount of radiation emitted by an object is governed by the Planck equation:

$$L(\lambda, T_{BB}) = \varepsilon \frac{2c}{\lambda^4} \cdot \frac{1}{e^{hc/\lambda k T_{BB}} - 1} \quad , \quad (3)$$

where $L(\lambda, T_{BB})$ is the spectral radiance, defined as the photo flux per unit projected area per solid angle and per unit wavelength. λ is the wavelength, h is the Planck's constant, c is the speed of light, k is the Boltzmann constant, T_{BB} and ε are the temperature and emissivity of the object, respectively. Integration equation of Eq. (3) over the variable wavelength yields the Stefan-Boltzmann equation:

$$P = \varepsilon \sigma T_{BB}^4 \quad , \quad (4)$$

where P is the total emitted energy radiation power density per area, σ is the Stefan-Boltzmann constant. Eq. (4) clearly shows that the temperature T_{BB} and emissivity ε of the object determine the radiation power density. As P is proportional to T^4, a low background can be obtained by reducing the temperature of background objects. Therefore, placing all involved instruments in cryogenic environment is a valid way to build the low-background spectrometer system.

According to Eq. (4), emissivity is the other decisive parameter for radiation power density. It is a constant between 0 and 1, and the value is affected by material, surface condition, reflectivity, and opacity of the object. In steady-state, the total energy acts on an objects satisfies: reflectivity + transmissivity + absorptivity = 1 and absorptivity = emissivity. If the object is opaque, the emissivity of a surface could be given as emissivity = 1 − reflectivity, which means that a high reflectivity will results in low emissivity and low radiation. Therefore, employing opaque instruments with high reflectivity in a FTIR can effectively cut down the radiation emitted from the system itself.

For a detector equipped in FTIR, background radiation originates from adjacent objects it can "see" including interferometer, source port and detector port. Radiation from the interferometer is easily collimated and focused onto the detector due to its specific location. Radiation from the source port, such as source package and holder, is another important source of background. In addition, radiation from the detector package and holder can also enter the interferometer, then reflect back and contribute to the background. Stray light from other surrounding objects can be detected as well, but this contribution is usually much smaller. Therefore, to achieve weak signal detection, radiation from the interferometer, detector and source should be suppressed.

In traditional Michelson FTIR, radiation from the interferometer (e. g., mainly from beamsplitter) and optical lenses is an important part of background radiation. Emissivity of these components can't be made very low across a broad wavelength range. Hence, besides the source and detector, interferometer and optical lenses have to be cooled down for a low-background Michelson spectrometer, which requires complicated cryogenic shields. This configuration is by no means easily achieved. Therefore, it is critical to simplify the low-background configuration by cutting down radiation from the interferometer in a simple way.

2 Design

The schematic diagram of the low background LGI spectrometer is shown in Fig. 2 (a). Two parabolic mirrors (the input and output mirrors) are employed to guide light beams. The source and detector are placed at the focus of these two mirrors, respectively. At the input mirror, radiation from the source is caught and converted to be a diffraction limited parallel beam towards the grating fingers. After reflected by grating, the beams are collected and focused onto detector by output mirror. Lamellar grating is the main feature, which is a binary grating operating in the 0th order[14]. It is composed of two sets of comb fingers, one set is fixed and the other is movable, as illustrated in Fig. 2 (b). The incident beams are partly reflected by the fixed parts and partly by the movable parts, which creates the wavelength-dependent diffraction pattern. LGI requires that geometry of source is approximate to a point source and highly coherent. So, for extended sources an entrance pupil should be added to produce the well-defined incident beams[10]. In addition, an exit slit should be added in the focal plane of the output mirror and in front of the detector, which can increase the bandwidth. The size of exit slit is decided by the minimum wavelength to be measured, as it should be designed small enough to cut off any first-order diffracted beams for wavelength longer than the minimum wavelength[10-11].

In a lamellar grating spectrometer, background radiation from the interferometer could be neglected when parabolic mirrors and grating fingers are polished smoothly and coated with metal e. g., golden is preferred. Because gold coated mirrors are near perfect, they have reflectivity close to 100% and almost zero emissivity. Then, in a LGI FTIR the background is mainly induced by radiation from the source port and detector part. Therefore, a low-background lamellar grating spectrometer could be obtained simply by placing only the source and detector in cryogenic shields, as the shadow parts shown in Fig. 2 (a). One point worthy noting is that the entrance pupil and exit slit should also be placed in cryogenic environment to prevent radiation of their own. The cooled exit slit, which controls the throughput of spectrometer, can also prevent most stray light from the surroundings at ambient temperature. The other point is that windows used in cryogenic shields may have emission as well. In such case, one possibility is to abandon windows if the entire system under vacuum and the other choice is to use windows with appropriate coating so that it has close to 100% transmission in the relevant wavelength region.

Compared to conventional Michelson spectrometer, the lamellar grating spectrometer has several differences. First, lamellar grating functions as both beamsplitter and reference mirrors in Michelson interferometer, which makes it compact and robust. Subsequently, LGI divides the wavefront of incoming radiation by the grating, instead of splitting radiation amplitude at a beamsplitter as in Michelson interferometer. Then, the measured wavelength range is determined by the operation range of beamsplitter material or coatings in Michelson interferom-

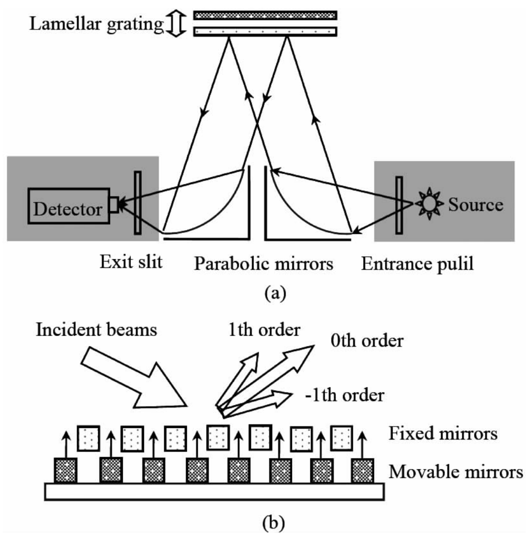

Fig. 2 (a) Layout of the lamellar grating spectrometer, the shadow parts represent instruments which should be cooled down for building a low-background LGI spectrometer (b) Working principle of the LGI

图2 (a) 反射光栅型光谱仪示意图,阴影部分代表建立一个低背景光栅型光谱仪需要降温的部分 (b) 反射光栅型干涉仪原理示意图

eter, which could be a limitation, especially in far-infrared spectrometry, as the conventionally used lenses and beamsplitter (e. g., Mylar beamsplitter or the wire-grid polarizer) exhibit strong dispersion and then have low efficiency. However, in LGI, the range is decided by grating period. Gratings can have the optimal efficiency close to 100% and can operate over a wide spectral range. Also, without a beamsplitter, LGI is non-dispersive and insensitive to vibration noise.

For sensitive detection, the main advantage of lamellar grating spectrometer compared to Michelson spectrometer is the elimination of beamsplitter and optical lenses, which avoids the vast majority of radiation from the interferometer, then the LGI spectrometer has no need to cool the interferometer for building a low-background system, which is more refined and easier-to-build.

3 Performances

As talked above, there is nearly no radiation emitted from the interferometer in a lamellar grating spectrometer, therefore, a low

background is obtained when the source and detector devices are cooled by cryogenic shields. In order to discuss the performance more intuitively, we took typical HgCdTe detectors as example to analysis the performance of such design theoretically. HgCdTe detectors are the most commonly used cryogenic detectors for infrared applications[15-16]. Rogalski *et. al* has demonstrated that the BLIP temperature of HgCdTe detectors ($\lambda_c < 15$ μm) is not lower than 100 K facing 300 K background radiation in 30° field of view (FOV)[17]. So, the BLIP regime can be always reached for cryogenic HgCdTe detector, even when background is suppressed. Actually, both photoconductive and photovoltaic HgCdTe detectors can reach the performance described above and can be equipped in the low background spectrometer[17, 18]. Here, we took photoconductive detector as example to illustrate the performance of our design. The BLIP detectivity for HgCdTe photoconductive detectors is expressed as[17]

$$D^*_{BLIP}(\lambda) = \frac{\lambda\sqrt{\eta(\lambda)}}{2hc}\sin^2(\theta/2)^{-1/2} \times \left(\int \frac{2\pi c\varepsilon}{\lambda'^4[\exp(hc/\lambda' k_B T_{BB}) - 1]} d\lambda'\right)^{-1/2} \quad , \quad (5)$$

where $\eta(\lambda)$ is the absorption at a given wavelength λ, θ is the FOV angle. Typical parameters are used: FOV angle $\theta = 30°$, $\varepsilon = 1$ and $\eta = 0.7$. In Fig. 3, the calculated BLIP detectivity at different background temperature is shown as a function of the wavelength. It shows that with the background temperature dropping, the obtained detectivity increases significantly, which is more obvious for shorter wavelength. For example, for HgCdTe detectors with cutoff wavelength at 9 μm, the detectivity is 1.27×10^{11} cmHz$^{1/2}$/W facing 300 K background radiation, while for 77 K (liquid nitrogen temperature) background radiation, the detectivity is 7.11×10^{14} cmHz$^{1/2}$/W, which is improved by three orders of magnitudes. This calculation applies to photovoltaic HgCdTe detectors as well, only a coefficient of $\sqrt{2}$ should be added on the right of Eq. (5)[18]. According to Eq. (1), the SNR of lamellar grating spectrometer can be improved three orders of magnitude as well, which has important significance for weak infrared signal detection.

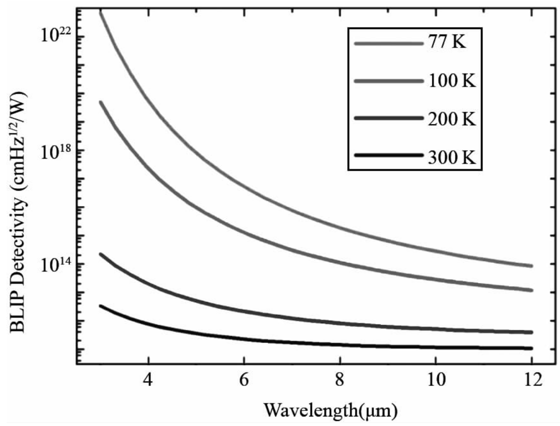

Fig. 3 For a photoconductive HgCdTe detector, the dependence of the BLIP detectivity on the wavelength for background temperature is 300 K, 200 K, 100 K and 77 K, respectively

图3 背景温度分别是 300 K、200 K、100 K 和 77 K 时,工作在背景条件限制下的光导型碲镉汞探测器的探测率和波长的关系

4 Conclusions

A novel low-background lamellar grating spectrometer design is proposed. Without beamsplitter and lenses, this design uses nearly perfect lamellar grating and mirrors to suppress the radiation from interferometer, then only the source and detector need to be placed in cryogenic environment. Due to the possible background radiation suppressed greatly, this design provides a solution of extremely sensitive detection. A simple estimation with HgCdTe detector shows that in a wide wavelength range ($3 \sim 12 \mu m$), the BLIP detectivity and the corresponding SNR of spectrometer can be improved at least three orders when the background radiation is reduced from 300 K to 77 K, and the improvement is especially obvious for short wavelength. In contrast to the low-background Michelson spectrometer available in literatures, the proposed design does not need to cool the interferometer, which is easier to implement and more beneficial to the widespread use of cryogenic spectrometer.

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