

LASER SPECTROSCOPY

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On the possibility of designing a high-resolution heterodyne spectrometer for near-IR range on the basis of a tunable diode laser

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Abstract. **The results of heterodyning of broadband radiation in the near-IR range are presented. A stabilised DFB laser was used as a local oscillator, while the role of a broadband radiation source was played by another DFB laser, excited by the pump current below its threshold value. A fibre-optical Y-coupler based on the single-mode silica fibre served as a diplexer. The radiation mixed in the single-mode fibre was incident on the photodetector, the role of which was played by a p–i–n photodiode. The signal from the photodiode was amplified by the preamplifier with the feedback resistance 240 kΩ and the bandwidth ~1 MHz and then digitised using a 16-digit ADC. The frequency scanning was implemented via the variation of the local oscillator frequency. The developed registration system provides the sensitivity ~1.4% of the shot noise value at the acquisition time ~40 min.**

Keywords: *heterodyning, diode laser, near-IR region.*

1. Introduction

High-resolution spectroscopy is a powerful analytical method widely used in space research, astrophysical observations, in applied problems of environmental and industrial pollution control, etc. High-resolution spectroscopic technique is most called-for in solving the problems of the analysis of rarefied molecular gases, where the relative homogeneous broadening of rotational lines in the IR region does not exceed 10^{-5}. Many urgent problems of the global climate monitoring, in particular, remote measurement of the content of greenhouse gases performed from a satellite orbit, may be solved only using the devices that can provide resolution of individual rotational lines in the near-IR spectral range [1].

The high spectral resolution ($\lambda/\delta\lambda \sim 10^7 - 10^8$) allows direct measurement of the velocity field in gas flows, as well as in atmospheres of the Earth and other planets, by detecting the Doppler shift of spectral lines. This is still implemented in a rather limited number of both surface and satellite-based devices [2–4]. Therefore, the necessity for compact and inexpensive instrumentation for spectral measurements with resolving power 10^7 and higher in the near- and mid-IR spectral ranges, which can be used in various fundamental and applied research, is extremely high.

The increase in spectral resolution is typically accompanied with lowering the radiation intensity, detected in a single spectral channel, which inevitably leads to the reduction of the signal-to-noise ratio in direct measurements. The only known method that allows avoiding the reduction of detection capability of the instrumentation, when increasing the resolution power, is the heterodyne detection. The essence of this technique is transferring the spectral interval under study into the intermediate frequency region at the expense of adding the detected signal to the radiation of a reference source [local oscillator (LO) or heterodyne] at a nonlinear detector (mixer). In this case, the noise is received by the registration system also in a relatively narrow range of intermediate frequencies, which allows obtaining satisfactory noise characteristics at a high spectral resolution.

While being widespread and serving as a basic technique for spectral analysis of signals in the microwave and terahertz spectral ranges, in the optical range the heterodyne detection is used much less often, in spite of the availability of high-stability lasers that may be used as LOs. In the first papers on laser heterodyning [5], the role of LOs was typically played by CO_2 lasers, while in recent years diode lasers (DLs) became widespread, which allowed substantial increase in the spectral range of useful signal detection [6, 7].

The main problems arising in the implementation of heterodyne detection of IR radiation may be divided into two groups. The first group includes the problems of creating low-noise and quick-response radiation detectors. In this field a substantial progress has been achieved in recent decades, mainly due to the development of p–i–n diodes widely used in telecommunications [8], as well as due to the creation of detectors based on 'hot' electron bolometers [9, 10]. It is worth noting that the heterodyne detection of IR radiation does not require special nonlinear mixers, since the signal at the detector is proportional to the absorbed power, i.e., the square of the electric field strength.

The second group of problems is related to the difficulty of providing the coincidence of wave fronts of the signal and the LO radiation. Efficient transformation of the heterodyne signal into the intermediate frequency region requires high quality of the wave front, which is commonly provided by a diplexer, a special device overlapping the signal beam and the radiation from the LO. The diplexer is the finest optical element

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of the existing heterodyne spectrometers in the optical region, and the required quality of the wave front reduces the geometrical aperture of these devices up to the limits of diffraction resolution of earth-based telescopes [11]. In our case, thanks to beams overlapping in a single-mode silica fibre, the condition of the wave-front coincidence is automatically fulfilled.

We find it interesting to study the possibility of designing a heterodyne spectrometer operating in the near- and mid-IR regions, which under appropriate calibration and acquisition time could measure a signal with the power as small as a fraction of the shot noise power. The demonstration of possibility to construct a relatively simple optical system, implementing such characteristics and providing the spectral resolution no less than 10^6, is the aim of the present paper.

2. Experimental setup

As mentioned above, one of the main problems of heterodyning in the near-IR range is associated with strict alignment requirements to the coincidence of the signal and LO radiation wave fronts. This problem is removed if radiation propagates in a single-mode waveguide. That is why in the present work we use a Y-coupler based on a single-mode silica fibre. Besides, the proposed scheme differs from the classical one by the absence of intermediate-frequency spectrum analyser, since, as will be demonstrated below, the spectral sweep is implemented at the expense of scanning the LO frequency. The block diagram of the experimental setup is presented in Fig. 1.

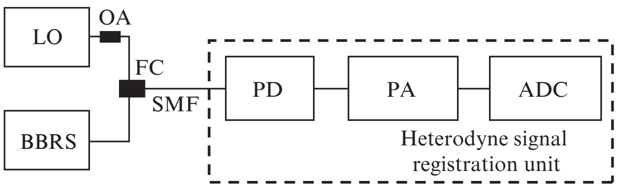

Figure 1. Block diagram of experimental setup: (BBRS) broadband radiation source; (OA) optical attenuator; (FC) fibre coupler; (SMF) single-mode fibre; (PD) photodiode; (PA) preamplifier.

The setup consists of the LO, the optical attenuator, the source of broadband radiation, the fibre coupler and the unit of the heterodyne signal registration, which incorporates the photodiode (PD), the preamplifier (PA) and the ADC.

A tunable 1.392-μm DFB laser (NTT Electronics) with a fibre pigtail was used as a LO. To eliminate the feedback we used the FC/APC connector. By means of the attenuator one could control the power of radiation incident on the PD.

Two sources of broadband radiation were used in the experiments, the analysis of their spectra being the problem to be solved by means of the proposed heterodyne spectrometer. These sources were two semiconductor DFB lasers with a fibre output of radiation (NEL) at λ = 1.392 μm (Source 1) and λ = 1.357 μm (Source 2). They were excited by the pump current below the threshold value. Figure 2 presents the emission spectra of the LO excited by direct current and of the broadband sources, measured using the laboratory Agilent 86143B spectrum analyser with the resolution 1 nm. The power of LO radiation in the experiment was 10 μW. Note, that the frequencies of the radiation from the LO and Source 1 in the lasing regime are similar and that the range of LO

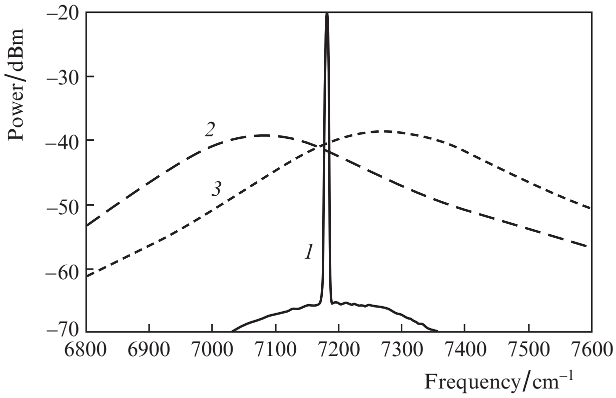

Figure 2. Emission spectra of the LO (*1*) and broadband sources 1 (*2*) and 2 (*3*) at a constant pump current.

frequency scanning is located in the spectral region of Source 1, but far beyond that of Source 2.

To control the LO frequency, we used two regimes of DL operation. In the first regime the pump current of the laser was modulated by saw-like pulses with the duration 6 ms and the repetition period 10 ms, so that the dead time was 4 ms. Since the frequency of DL radiation depends on the pump current, the LO radiation frequency was modulated by a quasi-linear periodic time dependence with the tuning range up to 3 cm^{-1} (pulsed regime) [12]. In the second operation regime the LO pump current was direct (DC regime), and the frequency scanning was implemented via the slow variation of the DL temperature. When changing the temperature from 4 to 50 °C, the laser radiation frequency was tuned from 7162 to 7194 cm^{-1}.

The radiations from the LO and the broadband source entered the two inputs of the Y-coupler and were mixed in the output single-mode fibre (see Fig. 1). At the output of the single-mode fibre the p–i–n diode with a fibre input (Hewlett Packard, PDT0313-FC-A) was installed. The signal from the PD was amplified by the PA having the feedback resistance R = 240 kΩ and the bandwidth B = 1 MHz and then digitised by means of the 16-digit ADC, a part of the board (National Instruments) operating at the clock frequency 111 kHz. The range of voltages measured by the board ranged from 0 to 5 V. The developed software allowed registration of the PD signal and the level of its noise versus the pump current (Fig. 3), as well as their averaging. The time of a single measurement was determined by the current pulse duration and was equal to 10 ms. Averaging of the obtained results could be performed over the time interval from 100 ms to tens of minutes. When measuring noises, for each value of the pump current the noise component of the signal, i.e., the difference between the recorded signal and the noiseless (averaged) one, was determined. The variance of the noise component was averaged over the realisations.

For pump currents exceeding the threshold value of 7 mA the signal from PD, detecting only the radiation from the LO, is linearly dependent on the pump current. Switching on the source of broadband radiation, excited by direct current, leads to the shift of the signal by 0.4 V.

The PD noises at currents below the threshold are determined by the noises of the registration unit (Fig. 1), and at currents above the threshold by the shot noises of photocurrent (see below). Switching on the broadband radiation source

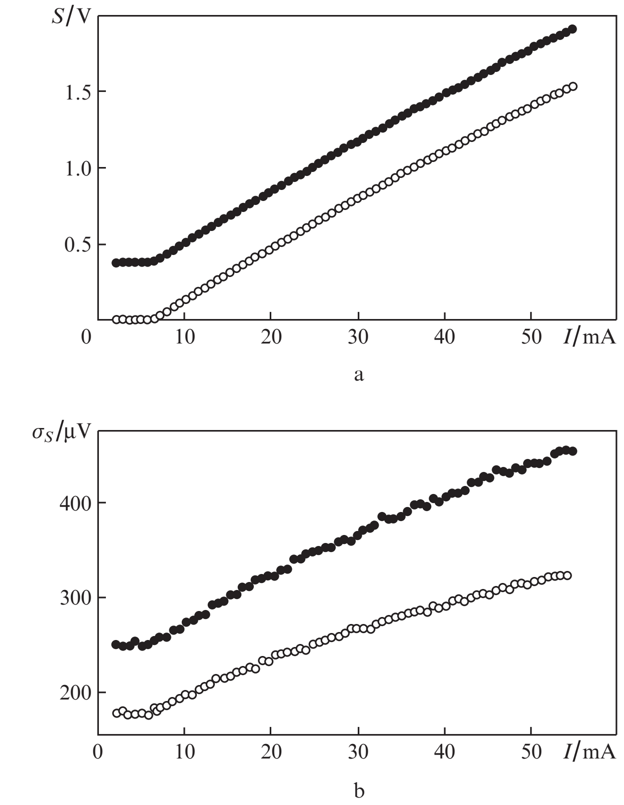

Figure 3. Dependences of the signals S (a) and their root-mean-square deviations (b) on the pump current I with the broadband radiation source switched off (○) and on (●). The LO operated in the pulsed regime.

leads to the increase in noises for the pump currents both lower and higher than the threshold.

3. Heterodyne signal

Consider the radiation incident onto the unit of the heterodyne signal registration. Let $E_{\rm LO}$ and $E_{\rm s}$ be the electric field strength for the coherent and broadband signal radiation at the PD, respectively

$$E_{\rm LO} = E_{{\rm LO}\omega}\exp(-{\rm i}\omega_{\rm LO}t),$$
$$E_{\rm s} = \int_0^\infty E_\omega \exp(-{\rm i}\omega t)\,{\rm d}\omega. \quad (1)$$

The PD measures the photocurrent i, determined by the intensity of the incident radiation

$$i = K[|E_{\rm LO}|^2 + (E_{\rm LO}E_{\rm s}^* + E_{\rm LO}^*E_{\rm s}) + |E_{\rm s}|^2], \quad (2)$$

where K is the sensitivity of the photodiode. The recorded signal U is determined by the PD current (2) and the feedback resistance of the PA:

$$U = Ri. \quad (3)$$

The first and the third terms in the square brackets in Eqn (2) are the steady signals caused by the LO and signal radiation, respectively. The second term is the analytical heterodyne signal:

$$(E_{\rm LO}E_{\rm s}^* + E_{\rm LO}^*E_{\rm s}) = {\rm Re}\int_0^\infty E_{{\rm LO}\omega}E_\omega \exp[-{\rm i}(\omega_{\rm LO} - \omega)t]\,{\rm d}\omega. \quad (4)$$

In the region of sufficiently low frequencies the useful heterodyne signal represents a white noise with the spectral density $E_{{\rm LO}\omega}E_\omega$ (4).

The analytical noise heterodyne signal is determined also by the bandwidth B of the PA transmission, while its root-mean-square deviation is given by the expression

$$\sigma_S^{\rm het} = RK\sqrt{B}\,E_{{\rm LO}\omega}E_{\omega_0} = R\sqrt{B\frac{2i_{\rm LO}i_{\rm s}}{\Delta\omega}}. \quad (5)$$

Here $i_{\rm LO}$ is the photocurrent determined by the radiation from the LO; $i_{\rm s}$ is the photocurrent determined by the radiation of the broadband source (Fig. 3a); $\Delta\omega$ is the effective width of the signal radiation spectrum in the region of the DL frequency scanning; E_{ω_0} is determined by the spectral density of the signal radiation at the LO frequency.

Alongside with the heterodyne noise, the additional noises also exist, namely, the parasitic noise of the registration unit (Fig. 1), the shot noise of the photocurrent, and the noise of the DL radiation.

The noise of the signal (3) caused by the shot noise of the photocurrent is determined by the equation [13]

$$\sigma_S^{\rm SN} = R\sqrt{ei_{\rm LO}B}, \quad (6)$$

where e is the electron charge. The voltage of the shot noise has the same dependence on the feedback resistance, the PA bandwidth and, most importantly, on the power of LO radiation, as the voltage of the heterodyne noise [Eqn (5)]. Therefore, the parameters of the experimental setup should be chosen such that the noise of the signal is mainly caused by the shot noise [14].

Figure 4 shows the root-mean-square deviations of the current of different components of the signal noise versus the photocurrent for optimal parameters of the setup (see below). It is seen that at large values of the photocurrent i the noise

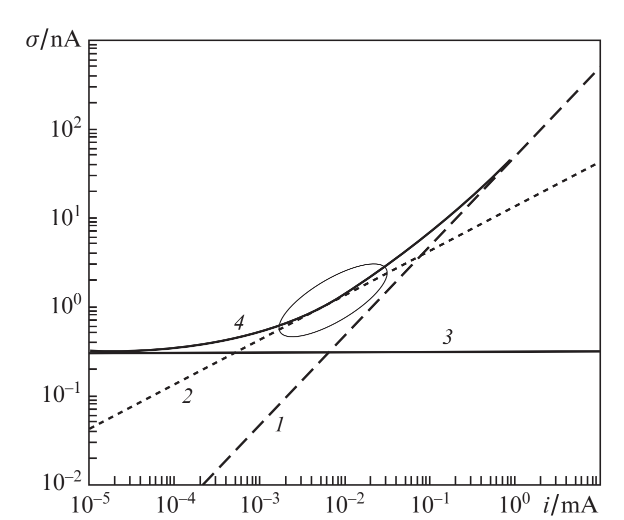

Figure 4. Dependences of root-mean-square deviations of the LO radiation noise current (*1*), the shot noise of the photocurrent (*2*), the registration unit noise (*3*), and the total noise of the system (*4*) on photocurrent.

of the signal, proportional to the photocurrent, begins to dominate over the shot noise. At small values of i the noise of the registration unit prevails, which does not depend on the photocurrent. Hence, the optimal range, in which the shot noise of the photocurrent prevails, is the range $i = 2-20$ μA (curves inside the ellipse in Fig. 4), which corresponds to the LO radiation power at the PD from 2 to 20 μW. For the typical DL power of 20 mW this means that 0.01%–0.1% of the DL radiation should be incident on the PD. In the present experiment the reduction of radiation power was implemented using an attenuator (Fig. 1).

Consider different components of the noise introduced by the registration unit, namely, the PD noise, caused by the PD dark current; the noise due to ADC discreteness; the thermal noise of the PA feedback resistance; the current and voltage noises of the chip, used in the present PA; and the shot noise of the photocurrent.

Figure 5 presents spectral densities of the noise voltages G of the optimised PA, calculated for the setup with the following parameters: the LO power $P = 10$ μW, the photocurrent $i = 10$ μA, the PA transmission bandwidth $B = 1$ MHz. In Table 1 the voltages for different components of the noise, introduced by the heterodyne signal registration unit, are summarised.

From the results of simulation it is seen that, as it was intended, the major contribution to the noise characteristics of the setup comes from the shot noise of the photocurrent. Hence, when the receiver bandwidth is narrow (10^6 Hz), the quantity to be measured is the noise component. However, in this case the registration of wider spectra requires LO frequency tuning (5). In this connection the DFB laser, excited by saw-like pulses of the pump current, was used.

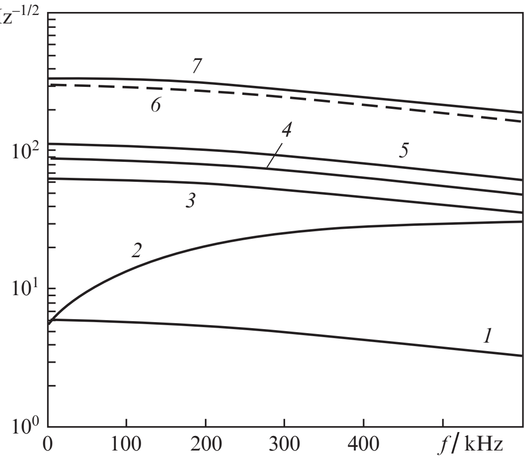

Figure 5. The results of simulation of voltage spectral densities for different components of the heterodyne signal registration unit noise: the PD noise (*1*), the chip voltage noise (*2*), the thermal noise of the feedback resistance (*3*), the chip current noise (*4*), the LO intensity noise (*5*), the shot noise of the photocurrent (*6*), and the total noise of the registration unit (*7*).

Table 1. Voltages of different components of the heterodyne signal registration unit noise.

Noise component	Noise voltage/mV
Photodiode noise	7
Chip voltage noise	49
ADC discreteness noise	34
Thermal noise of resistance	73
Chip current noise	106
Shot noise	335
Total noise	362

The method of heterodyne signal registration in the narrow band of PA frequencies (~1 MHz) is relatively new in optical heterodyning and allows significant simplification of the experimental scheme, since it implies no analysis of the intermediate frequency spectrum

Using Eqns (5) and (6), we derive the expression for the signal-to-noise ratio:

$$\frac{D^{\text{het}}}{D^{\text{SN}}} = 2\frac{i_{\text{s}}}{e\Delta\omega}, \tag{7}$$

where D^{het} and D^{SN} are the variances of the heterodyne and shot noise, respectively. One can see from Eqn (7) that the power of the heterodyne signal may be measured in the units of the shot noise power. The variance of the noise voltage, in contrast to the root-mean-square deviation of the voltage, is linearly dependent on the pump current and, therefore, will be used to analyse the experimental results.

The minimal detectable signal is determined by the height of the 'grass' of the curve in Fig. 3b (dark points), which decreases inversely proportional to the square root of the acquisition time. Thus, optimising the acquisition time, one can measure signals, for which the ratio (7) is much smaller than unity, i.e., it is possible to overcome the fundamental measurement limit, determined by the shot noise of the photocurrent.

4. Experimental results

As already mentioned, the DL frequency scanning may be implemented by varying either its temperature (DC regime) or the pump current (pulsed regime).

Figure 6a shows the emission spectrum from Source 1, obtained by heterodyne detection with the LO operating in the DC regime. The temperature of the LO active zone was changed from 4 to 50°C, providing the frequency scanning within 22 cm^{-1}. The frequency scale was calibrated using several known absorption lines of water, whose position was previously determined using the methods of laser-diode spectroscopy [15]. The power of the heterodyne signal is presented in the units of the shot noise power. It is seen that is amounts to 15%–40% of the shot noise power. The spectral density of the input radiation power in this case is equal to ~10^{-20} W Hz^{-1}.

In addition, the emission spectrum from Source 1 was measured using the laboratory spectrum analyser (Fig. 6b) with the resolution 0.06 nm. It is seen that the spectrum of the heterodyne signal completely repeats the spectrum of Source 1. The observed spectrum reflects the mode structure of the radiation of the source, which manifests itself even below the lasing threshold.

For further investigation of the described method we used Source 2, whose spectral region is beyond the region of LO frequency scanning. Thus, the influence of the mode structure of the source radiation was minimised. The measurements were performed in the pulsed regime of DL operation, the range of LO frequency scanning amounting to ~0.8 cm^{-1}. First, the noise voltage variance was measured with the radiation source switched off, and then it was repeated with the source switched on. The results of the experiment are presented in Fig. 7, where the dependences of noise voltage vari-

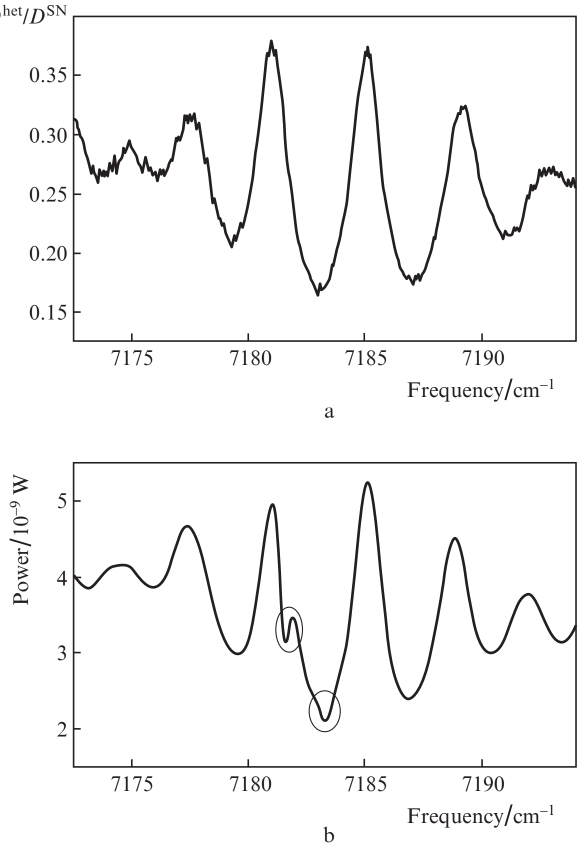

Figure 6. Emission spectra of Source 1, obtained using heterodyne detection in the DC regime of LO operation (a) and by means of a laboratory spectrum analyser (b). The absorption lines of water vapours, present in the volume of the spectrum analyser, are marked with ellipses.

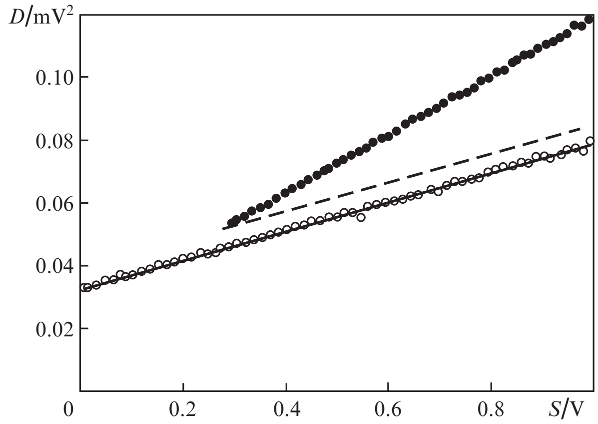

Figure 7. Dependences of noise voltage variances D on the PD signal with the broadband radiation Source 2 switched off (○) and on (•). The solid line presents the calculation based on the model of shot noise variance. The dashed line corresponds to the model with the shot noise and the homodyne noise of the broadband radiation taken into account.

ances on the PD signal, linearly related to the pump current [see Eqn (7)], are shown. It is seen that the obtained dependences are linear. This confirms the fact that the variance of both the heterodyne signal and the shot noise linearly depends on the value of the signal [see Eqns (5) and (6)].

The presence of steady signal radiation leads to the shift of the beginning of the straight line by 0.3 V to the right (Fig. 7). In this case the shot noise variance is determined by the photocurrent and is described by the same solid straight line. If the intensity of LO radiation is close to zero, than the noise voltages, measured with the source switched on, should coincide with those of the shot noise. In other words, the beginning of the line describing the measurements with the source switched on should lie on the straight line, corresponding to the shot noise. This is obviously not so. Therefore, the observed disagreement is due to the presence of an additional noise component. Seemingly, it is the homodyne noise of the broadband signal radiation. Such a noise mechanism produces a constant component with respect to the shot noise. The dashed straight line in Fig. 7 describes the total variance of the photocurrent shot noise and the homodyne noise of the signal radiation. The presence of heterodyne signal leads to the increase in the slope angle of the experimental straight line. Its variance can be found by subtracting the data, obtained using the model with both the shot and the homodyne noise taken into account, from those of the experiment.

In our experiment the ratio of the heterodyne noise variance to that of the shot noise (7) is equal to 0.5. The use of the acquisition procedure reduces the spread of the data, presented in Fig. 7. For the acquisition time 40 min the height of the 'grass' is 1.4% of the shot noise value. Hence, the analysed scheme of heterodyne signal detection provides the sensitivity ~1.4% of the shot noise value (or ~10^{-21} W Hz^{-1}).

Modern systems operating in the far- and mid-IR ranges, have not reached the 'shot limit'. The typical level of instrumental noises is 3–6 times higher than the shot noise level [6, 7].

5. Conclusions

The experiment described above has shown the efficiency of using a single-mode fibre coupler as a diplexer in heterodyning the broadband radiation in the near-IR spectral range. In the simplest scheme of heterodyne detection the scanning of the spectral range may be implemented by modulating the frequency of the LO, which in our experiment was a tuneable DFB laser. The radiation to be analysed was produced by DFB lasers, excited by the pumping current below the threshold value, which is necessary to provide laser oscillation. This allowed considering the heterodyne signal as a noise and provided significant simplification of the experimental scheme as compared with the classical approach, which requires the analysis of the intermediate frequency spectrum. By means of the constructed experimental setup, using the heterodyne method, we measured the spectrum of the radiation source that demonstrated good agreement with the spectrum, measured using the laboratory spectrum analyser. It is expected, that the spectral resolution, determined by the radiation line width and the stability of LO oscillation, will amount to ~2 MHz, which is equivalent to the relative resolving power of spectral measurements $\lambda/\delta\lambda \sim 10^8$. The simplicity of the developed scheme opens wide possibilities for high-resolution spectral measurements.

The developed scheme of detecting the heterodyne signal provides the sensitivity ~1.4% of the shot noise value, which corresponds to the spectral density of the input radiation ~10^{-21} W Hz^{-1} for the acquisition time ~40 min. This allows measurements of molecular absorption at the level of ~1%. Thus, the proposed scheme may be successfully used in the analysis of low-concentration gas impurities.

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