Application of step-scan FTIR to the research of quantum cascade lasers

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The principle of step-scan Fourier transform infrared (FTIR) spectroscopy is introduced. Double modulation step-scan FTIR technique is used to obtain the quantum cascade laser's stacked emission spectra in the time domain. Optical property and thermal accumulation of devices due to large drive current are analyzed.

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Fourier transform infrared (FTIR) spectroscopy has more advantages over many other techniques for high resolution studies in the mid-infrared and far-infrared spectral ranges. In addition to the high frequency resolution, it exhibits a high signal-to-noise ratio (SNR), high throughput, and broad band range. There are two ways for the spectrometer to implement the scan process, i.e., the rapid-scan (continuous-scan) mode and the step-scan mode. Although many relatively simple rapid-scan FTIRs have been used successfully in the past years, there is a resurgence of interest in step-scan FTIR in the last decade[1−5]. This fact results from the advantages of step-scan FTIR over rapid-scan FTIR in two fields: the study of time-dependent phenomena and the experiments of double modulation for weak signal. In this paper, we use the time-resolved step-scan FTIR with double modulation to investigate the spectra of quantum cascade lasers[6].

The quantum cascade laser (QCL) is a mid-infrared unipolar light source based on intersubband electron transitions. Its active region is composed of multiple stages, and all these stages cascade together. Generally, the number of these stages arrives to several tens, so that a high drive power density is needed when the device is lasing. A pulse drive current at low duty cycle is generally applied to decrease the thermal accumulation in the active region during the research. There are two obstacles in the research of the quantum cascade laser emission spectrum. One is how to decouple the lasing signal from the background radiation and the electronics noise, the other is how to get the information of the time-dependent spectra. The background radiation is given in Fig. 1. In order to suppress the static background and amplify the needed signal, our spectral measurement system is arranged as Fig. 2. In this system we can get the time-dependent spectra killing two birds with one stone.

In Fig. 2, the quantum cascade laser is mounted epilayer down on the temperature-controlled cold finger of the liquid nitrogen cryostat and driven by a pulse generator in different duty cycles. The light emitting from the laser is coupled into the spectrometer through a CaF_2 lens and collimated by a concave mirror to the interferometer. The signal from the photovolt Hg-Cd-Te (MCT) detector after preamplifier can be directly coupled to the transient recorder board which is interfaced to the Fourier transform spectrometer or firstly sent to a digital signal processing lock-in amplifier by using a synchronous TTL output from the pulse generator as reference signal. In this paper, we use the former mode, where the synchronous TTL output from the pulse generator is used to trigger the transient recorder board. An oscilloscope is used to monitor the signal of the pulse generator in the experiment usually.

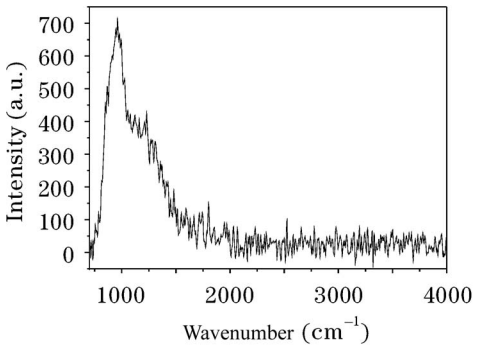

Fig. 1. Background radiation at room temperature.

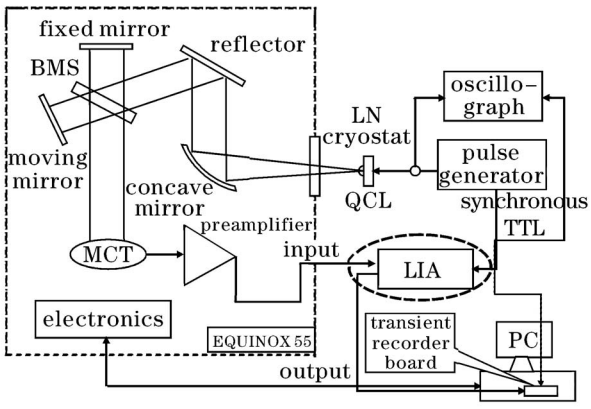

Fig. 2. The experimental setup for the measurement of the quantum cascade laser emission spectrum with a step-scan FTIR technology. BMS: beam splitter, MCT: Hg-Cd-Te, PC: personal computer, LN: liquid nitrogen, QCL: quantum cascade laser, TTL: transistor-transistor logic, LIA: lock-in amplifier.

During the measurement, the moving mirror of the step-scan FTIR spectrometer is stepped to a fixed position and held there, so that the optical path difference remains temporarily constant. In the time domain measurement, a reproducible experiment is initiated (i.e., repeatable impulses are provided to the laser by the pulse generator) and the signal is digitized in an equal interval (i.e., the time resolution). At each sampling position the signal can be averaged by putting some coadditions, so that the SNR will be enhanced by a factor of the square root of the coadditions number. After the data collection, the moving mirror is stepped to the next position and the process is repeated, when the mirror scan is completed, the signal intensity over the entire mirror position and time range is available, and the interferogram at a specific time can be extracted from the three-dimensional (3D) data array and Fourier transform. In this method the time resolution depends only on the signal strength, the rise time, sensitivity of the detector, and the speed of the data acquisition electronics, especially the A/D convertor. At the same time the step-scan mode excludes the problem of multiple Fourier frequencies, and the single internal modulation frequency introduced by the interferometer only depends on the servos and the electronics. There is a broad band modulation frequency for us to choose from and it is not necessary for the chosen frequency much higher than all the Fourier frequencies, which is necessary for the rapid-scan mode[7].

By the method mentioned above we got the emission spectra of our quantum cascade laser demonstrated in Ref. [8]. Using the information adhering to the spectra, we can investigate the thermal properties of the device. We applied a current pulse with a width of 1.5 μs and a repetition rate of 5 kHz to drive the laser. With a time resolution of 25 ns and a frequency resolution of 8 cm^{-1}, the result of Fig. 3 was gotten. Figure 4 is the emission spectra of different time in the same one cycle extracted from the stacked 3D picture.

Figure 3 shows an obvious intensity fluctuation of the emission in the current cycle. We attribute this phenomenon to the thermal activation of electrons into the continuum levels[9]. There are thermal accumulation and fluctuation in the active region when the laser operates and the thermal activation of electrons introduces the

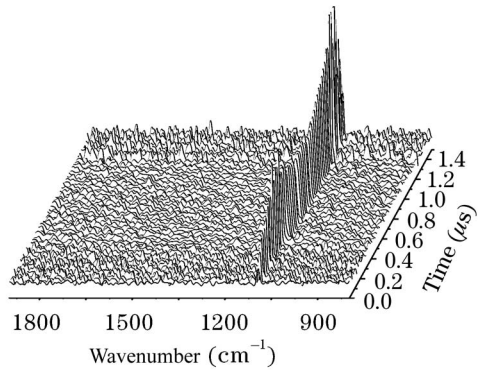

Fig. 3. Stacked electroluminescence spectra of a quantum cascade laser under liquid nitrogen temperature. The current cycle is 1.5 μs and the repetition rate is 5 kHz.

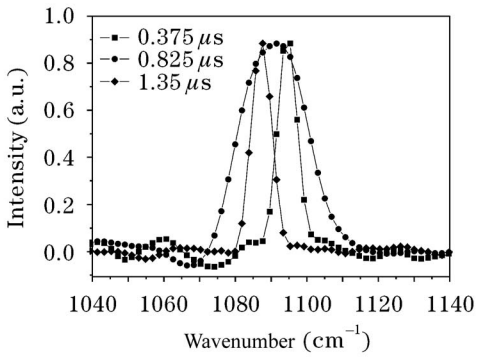

Fig. 4. Normalized emission spectra at different time extracted from Fig. 3.

gain fluctuation. Because of the little band-offset of materials, the effect of thermal activation in GaAs/AlGaAs quantum cascade lasers is notable, especially in higher temperature operation.

Figure 4 shows that the wavelength is about 9 μm and there is a red-shift in the current cycle. At the time around 0.825 μs, the full width at half maximum (FWHM) of the spectrum is much larger than others, this time region accords with the intensity valley in Fig. 3. The red-shift of spectral peak in the current cycle demonstrates the thermal accumulation and the expansion of FWHM in partial region indicates the gain fluctuation.

In summary, the application of the step-scan FTIR to the research of optical and thermal properties of quantum cascade lasers is an effective method and we will benefit from the deeper applied investigation of this technology.

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