COMPARATIVE STUDY OF THE BANDWIDTH OF PHONON-COOLED NbN HOT-ELECTRON BOLOMETERS IN SUBMILLIMETER AND OPTICAL WAVELENGTH RANGES

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Abstract

We report the results of the bandwidth measurements of NbN hot-electron bolometers, performed in the terahertz frequency domain at 140 GHz and 660 GHz and in time domain in the optical range at the wavelength of 395 nm. Our studies were done on 3.5-nm-thick NbN films evaporated on sapphire substrates and patterned into μm-size microbridges. In order to measure the gain bandwidth, we used two identical BWOs (140 or 660 GHz), one functioning as a local oscillator and the other as a signal source. The bandwidth we achieved was 3.5-4 GHz at 4.2 K with the optimal LO and DC biases. Time-domain measurements with a resolution below 300 fs were performed using an electro-optic sampling system, in the temperature range between 4.2 K to 9 K at various values of the bias current and optical power. The obtained response time of the NbN hot-electron bolometer to ~100-fs-wide Ti:sapphire laser pulses was about 27 ps, what corresponds to the 5.9 GHz gain bandwidth.

Introduction

The bandwidth of hot-electron bolometer (HEB) mixers has reached values which are record for bolometers. The gain bandwidth for phonon-cooled NbN HEB mixers of 4 GHz for 140 GHz and 650 GHz frequencies [1, 2] and the noise bandwidth of 8 GHz for 650 GHz [2] have been demonstrated. For diffusion-cooled Nb HEB mixers, the bandwidth has reached 6 GHz, when measured at 20—40 GHz [3]. However, there is a definite practical interest to even further extend the bandwidth of these devices. The possibilities of the HEB mixer technology in this direction are far from being exhausted. For example, the future of the NbN HEB technology requires that critical temperature $T_c > 10$ K and critical current density $j_c > 10^6$ A/cm^2 at 4.2 K are simultaneously obtained for d < 3 nm-thick films [1]. The reduction of the optimal power of the local oscillator P_{LO} below 100 nW leads to the decrease of the device length down to L < 0.2 μm, which, in turn, should bring an additional cooling channel for hot electrons—diffusion into metal contacts and a further bandwidth extension.

Once the very wide gain bandwidth of the mixer is achieved, one must face problems associated with the device characterization, since it is difficult to provide the necessary wide bandwidth connection for the output of the IF signal from the cryostat. In order to ensure the sufficient precision of the measurements, the bandwidth of the output line must be substantially (several times) greater than the mixer bandwidth with minimal losses and spurious resonances. Further problems arise when the device is operated at THz frequencies, since there is no data published about the gain bandwidth of HEB mixers at or above 1 THz, apparently due to the difficulty of smooth re-tuning of both the LO and the signal source in the sufficiently large frequency range. Some of the above difficulties can be avoided by measuring the noise bandwidth of the mixers, since it requires no tunable source and the Y-factor is measured as a noise ratio for the hot and cold loads. However, the noise bandwidth for HEB mixers usually does not coincide with the gain bandwidth, causing new technical problems—very low-noise amplifiers are needed for sufficiently high frequencies (in the range of 4-12 GHz).

The aim of this work is to study the gain bandwidth of NbN HEB mixers using a time-domain optical method, namely an electro-optical (EO) sampling technique [4]. EO sampling not only does not require output of the signal to be transmitted out of the cryostat, but the signal is measured in the close vicinity (below 100 μm) to the hot-electron bolometer connected into a coplanar waveguide. Thus, far larger bandwidth can be measured (the limit of the measurements is moved into the femtosecond/THz range) and the measurements are performed at optical frequencies, giving an independent comparison with the results obtained at hundreds GHz, and increasing our confidence that the bandwidth estimations for the terahertz range.

Experimental Techniques and Results

Ultrathin NbN films have been deposited on sapphire substrates by reactive dc magnetron sputtering in the $Ar+N_2$ gas mixture [5]. The maximum values of the critical film parameters (T_c and j_c) are reached at the discharge current value of 300 mA, the partial N_2 pressure of 1.7×10^{-4} mbar and the substrate temperature 850°C. The Ar pressure proved to have no substantial impact on the film deposition rate or film composition. For this reason, the pressure level is chosen in such way as to maintain a stable discharge, namely 4.5×10^{-3} mbar. The deposition rate is 0.5 nm/s, defined as the ratio between the film thickness, measured with a Talystep profilometer/profilograph and the deposition time. Structures of NbN HEB mixers for the frequency-domain measurements consist of several parallel strips 1-μm wide and 1-μm spaced. For patterning, a standard photolithography followed by ion milling was used. The strips were placed between Ti-Au contact pads 2-3 μm apart from each other. The number of NbN strips varied between 1 and 16, depending on the film thickness, to ensure that the normal-state resistance of the bolometer stayed within the 200-300 Ω range.

The device was mounted on a waveguide flange, as shown in Fig. 1. The experimental setup used for bandwidth measurements is presented in Fig. 2. Two BWOs operating at 120-145 GHz were used as the LO and signal sources. The LO and signal beams were coupled by a beam splitter and a beamguide into the cryostat. Two attenuators included in the quasioptical path allowed to adjust independently the signal and LO power, and to maintain the optimum LO power during re-tuning. The IF signal received from the mixer was amplified by a room temperature wideband amplifier (0.1-6 GHz) and sent to the input of the spectrum analyzer.

The results of the frequency domain investigations of the bandwidth of NbN HEB mixers are presented in Fig. 3. It must be noted that the obtained bandwidth values for ultrathin (d = 2.5-3.5 nm), high quality films. For films of lower quality, characterized by lower values of T_c and j_c at T = 4.2 K, the bandwidth was narrower than for the high quality films of the same thickness. At the same time, the data on the mixer bandwidth obtained at the 140 GHz frequency are fully confirmed by the measurements done at higher frequencies (660 GHz). In the latter experiments, a quasi-optical mixer was used, which was made of a spiral-antenna-coupled NbN HEB on a sapphire substrate.

For EO sampling measurements [6], we designed a simple, single-line, 5- to 10-μm long microbridge structure, in order to be treated as a point source of the photogenerated signal, so its resistance did not have to be matched to the impedance of our coplanar waveguide (CPW) transmission line. Since it is difficult to accurately terminate the transmission line for broadband signals such as a picosecond electrical pulse and our CPW line was not long enough, we had only a 40-ps-long reflection-free time window for the EO measurements and had to deal with waveforms containing reflections from the transmission line ends.

The actual experimental structure for our EO sampling measurements (shown in Fig. 4) consisted of a 4-mm-long CPW with a 30-μm-wide center line and 5-μm-wide gaps to the ground planes. Gold contact pads for wirebonding were deposited on both ends. Typically, after processing, the bridges exhibited $T_c \approx 10.6$ K, a transition width 0.8 K, and a critical current $I_c \approx$ 800 mA at 4.2 K. The sample was mounted on a gold-plated alumina substrate, attached to a copper block inside an exchange-gas, liquid-helium dewar, with optical access through a pair of fused-silica windows. During measurements, the sample was in He exchange gas and the temperature was regulated in the 2- to 10-K range and stabilized to below 0.1 K by adjusting the intensity of the stream of He exchange gas and the temperature controller heater. One end of the CPW was wirebonded directly to a semirigid, 50-Ω coaxial cable, which was used to bring the signal out the dewar and, together with an 18-GHz-bandwidth amplifier and bias-tee, allowed us to observe the bridge response on a fast oscilloscope. As shown in Fig. 4, the entire sample structure was overlaid with an electro-optical $LiTaO_3$ crystal to facilitate the EO sampling measurements.

The complete experimental setup of the EO system is shown in Fig. 5. A commercial Ti:sapphire laser, pumped by an Ar-ion laser, was used to excite picosecond pulses in the microbridge and electro-optically measure the propagating transient. The laser provided ~100-fs-wide optical pulses with 800-nm wavelength and 76-MHz repetition rate, at an average power of 1 W. The beam was split into two paths by a 70/30 beamsplitter. The first (excitation) beam (700 mW) was frequency doubled in a nonlinear β-Bariumborate (BBO) crystal, and a reflective filter was used to eliminate the remaining 800-nm light. The excitation beam was intensity modulated by an acousto-optic modulator and focused by a microscope objective to a 10-μm-diameter spot on the microbridge. The microscope objective is also a part of the viewing and beam positioning arrangement. The average optical power of the 400-nm light, measured at a position just outside the dewar, was ~0.75 mW. By measuring the amount of light absorption/reflection in the two dewar windows and the $LiTaO_3$ crystal, we found that the incident power was further reduced to ~0.37 mW at the NbN detector surface, corresponding to a fluency of 8.5 $\mu J/cm^2$. Taking the geometry as well as the reflectance and transmittance of NbN into account, we estimate the power actually absorbed by the microbridge was only ~3.5 μW, which could result in only minimal, well below 0.1 K increase in the bridge temperature.

Figure 6 shows the photoresponse of an NbN sample, obtained using the EO sampling technique. The measurements were performed at 8.9 K (T_c = 10.6 K), with the bridge bias current I ≈ 200 mA. The fine line in Fig. 6 represents the experimentally recorded transient, while the thick one is the computed average. Since our reflection-free window was only 40 ps, the observed response is a superposition of the main signal and the end reflections. This may explain the relatively long (30 ps) time of the signal build-up. A comparative study of several response waveforms showed that the signal decay time had approximately the same duration of 27±5 ps, which we can associate with the cooling time of the electron subsystem in thin NbN films. The calculated corresponding IF bandwidth is 5.9±0.9 GHz, a bit wider than that obtained in frequency domain measurements. The discrepancy between the two results is, however, not drastic and seems to be caused by limitations of both techniques. In the frequency-domain technique, the measurements above 4 GHz are complicated by the resonances which appear in the IF signal tract, while the EO sampling technique in the above 10-ps-time range is hampered by signal reflections. In fact, the latter technique works better for considerably shorter response signals [4], or specially designed, reflection-free test beds are needed. In future, we plan to manufacture samples imbedded in a long CPW, which in addition will contain matched loads on both ends of the line, helping to reduce (ideally, suppress completely) the reflected signals. Such arrangement should enable us to obtain the intrinsic relaxation time of NbN HEBs.

Conclusions

We have conducted comparative measurements of the gain bandwidth of NbN HEB mixers. The results obtained by the two techniques—frequency-domain measurements in the 140-650 GHz range and time-domain measurements in the optical range—allow one to give a very accurate estimate of the bandwidth attainable by the HEBs at this stage of NbN thin-film technology. This bandwidth is 4 to 5 GHz and, as EO sampling technique indicates, it could be substantially further extended, as well as should not decrease for HEB mixers operating in the THz frequency range.

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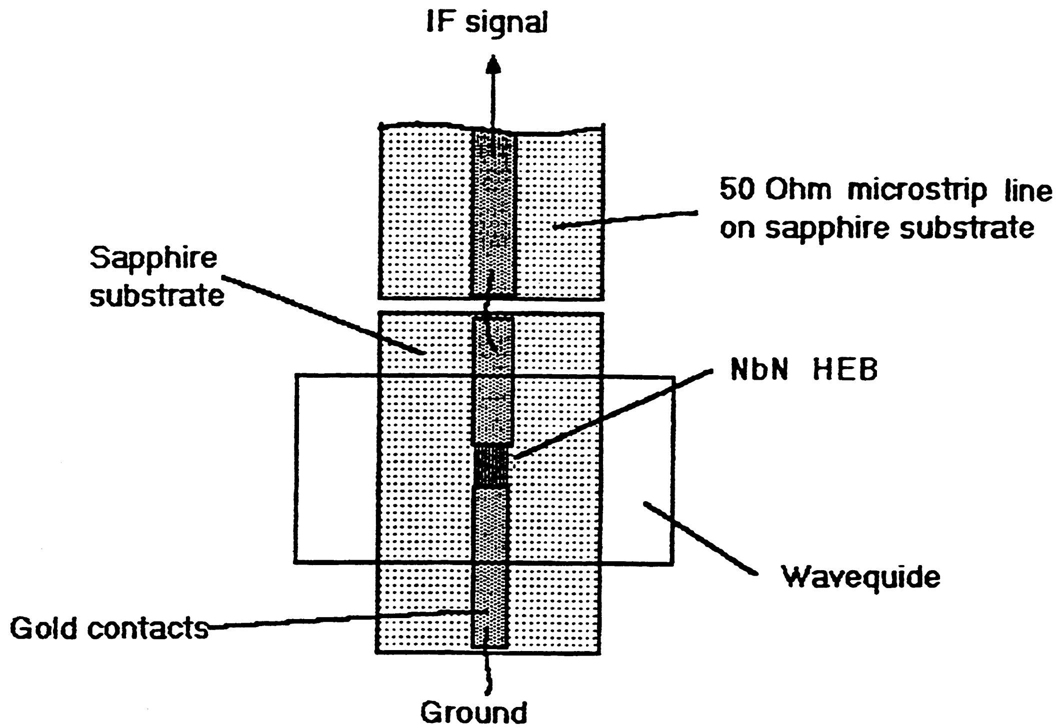

Fig. 1 View of the mixer chip on the waveguide flange.

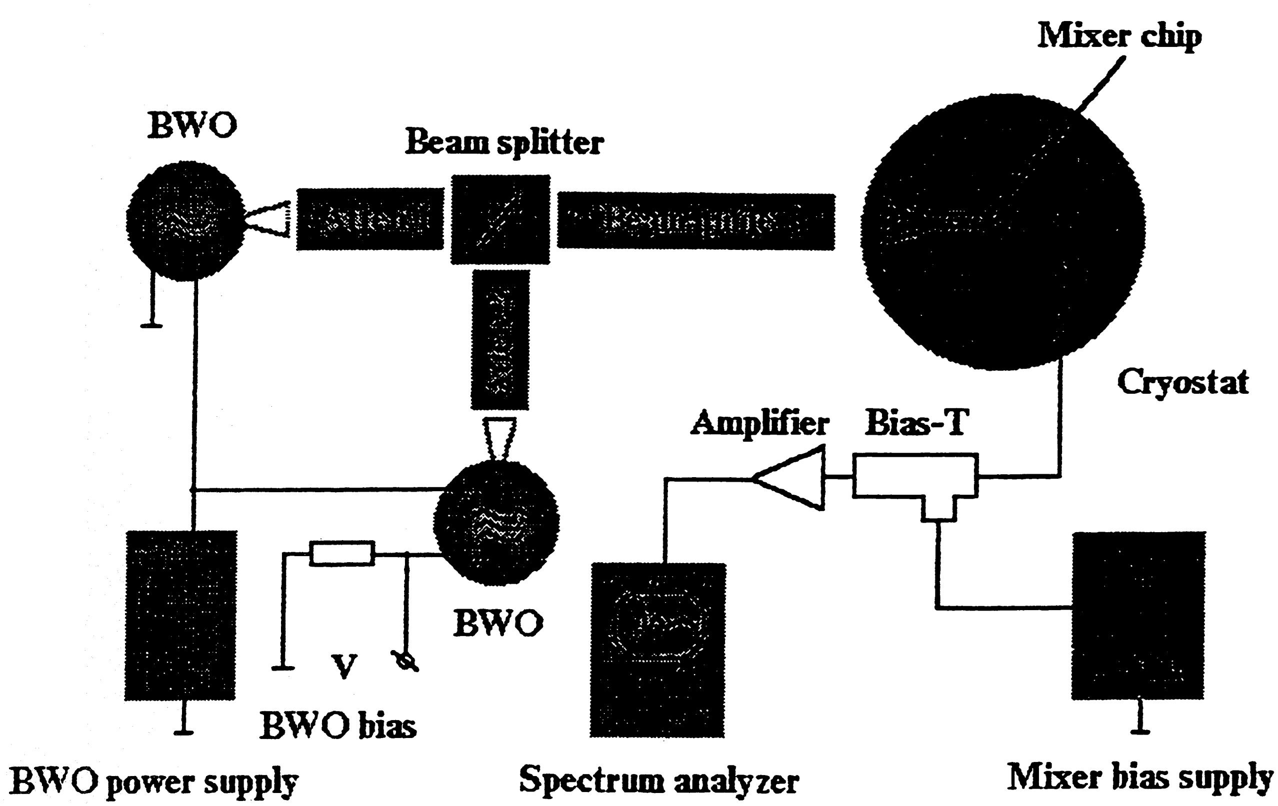

Fig. 2 Set-up for bandwidth measurements.

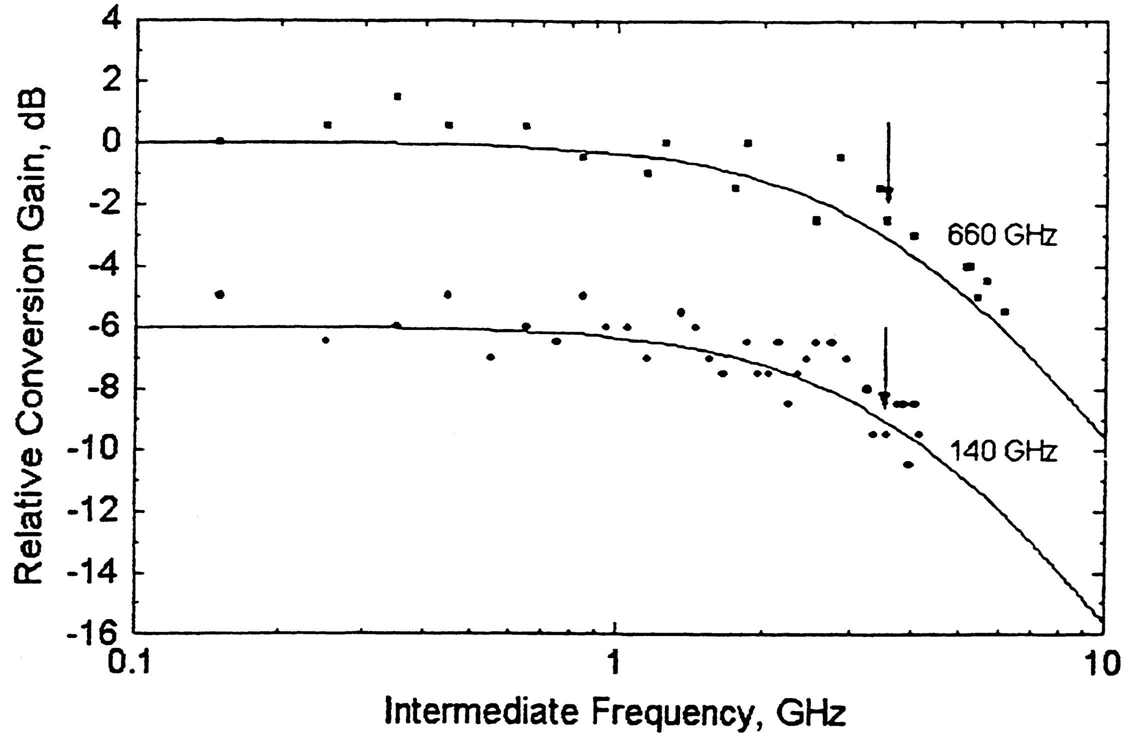

Fig.3 Relative conversion gain for NbN device measured at 140 and 660 GHz under optimal LO and dc bias.

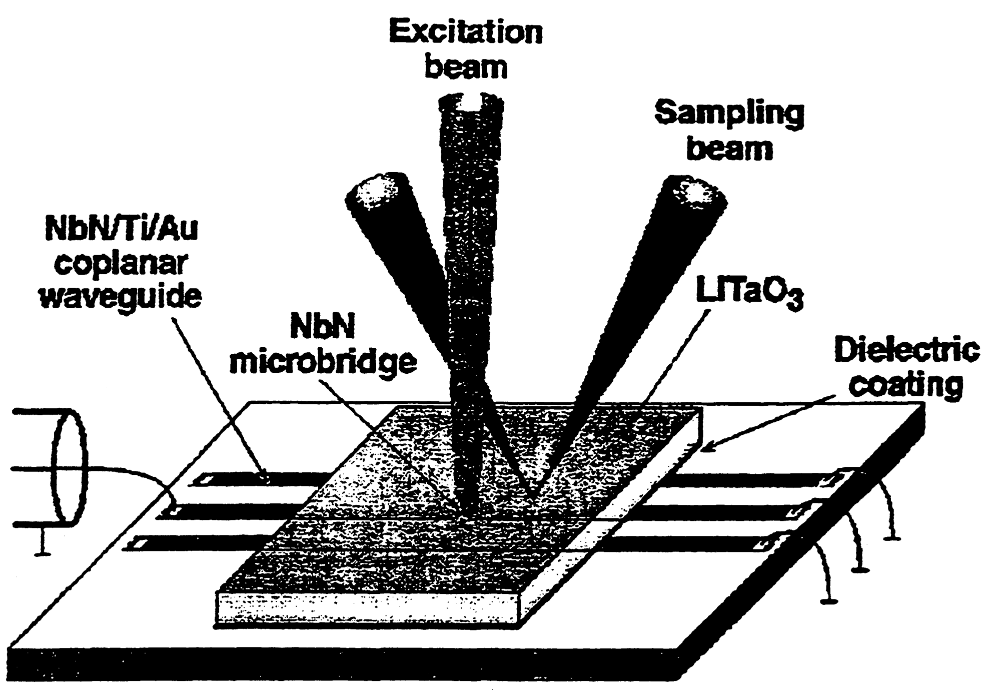

Fig.4 Electro-optic sampling is performed by covering the NbN microbridge with $LiTaO_3$ crystal.

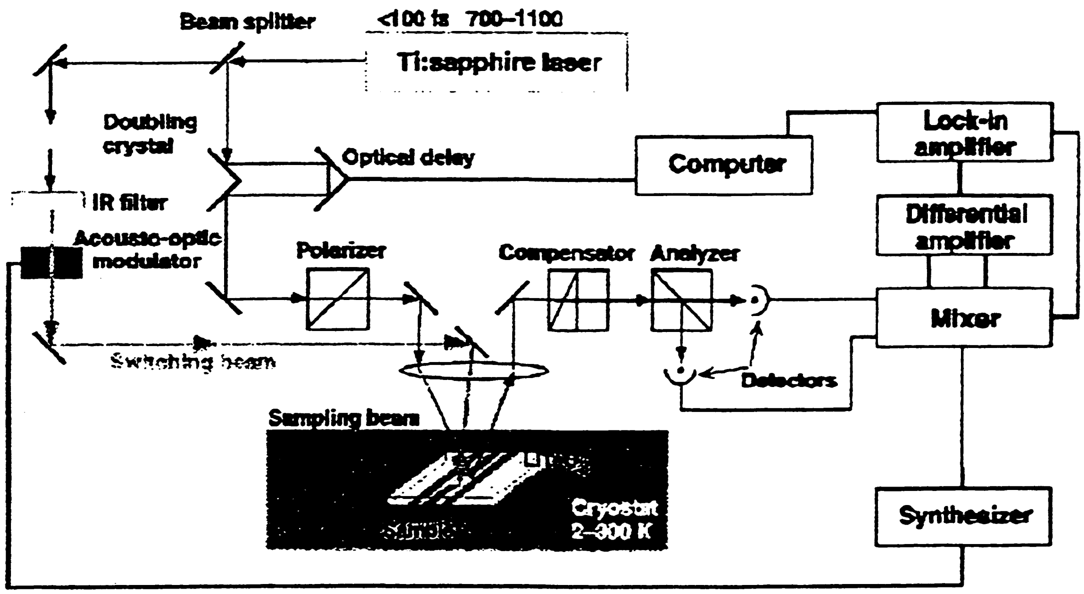

Fig.5 The cryogenic electro-optic sampling system measures ultrafast electrical transients.

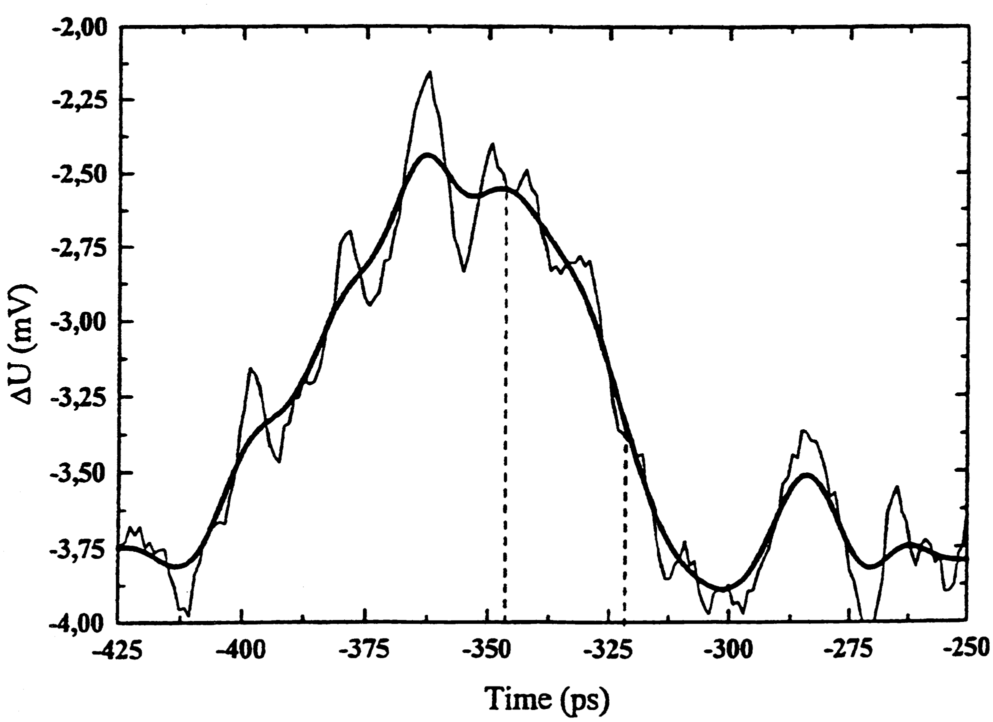

Fig. 6 Photoresponse of a NbN film at 8.9K measured with an EO sampling system.