Ultrafast Photoresponse in Microbridges and Pulse Propagation in Transmission Lines Made from High-$T_c$ Superconducting Y–Ba–Cu–O Thin Films

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Abstract—We report our femtosecond time-resolved measurements of the photoresponse of microbridges in YBa$_2$Cu$_3$O$_{x-}$ (YBCO) thin films, performed using an electrooptic sampling technique. Our test structures consisted of 5-μm-wide, 7-μm-long microbridges, incorporated in 4-mm-long coplanar waveguides, fabricated in 100-nm-thick, high-quality epitaxial YBCO films grown on LaAlO$_3$ substrates by laser deposition. When varying the biasing conditions between the superconducting and switched states, we observed transients of single-picosecond duration that corresponded to the nonequilibrium kinetic-inductance and the electron-heating response mechanisms, respectively. In both cases, experimental waveforms could be accurately simulated using a nonequilibrium (two-temperature) electron-heating model. From the fits, the YBCO intrinsic temporal parameters associated with the nonequilibrium conditions were extracted. The electron thermalization time was found to be 0.56 ps in the state above the material’s critical temperature ($T_c = 89$ K) and 0.9 ± 0.1 ps in the superconducting state at temperatures ranging from 20 to 80 K. The electron-phonon energy relaxation time was found to be 1.1 ps. The single-picosecond pulse distortion due to propagation on a YBCO coplanar waveguide was also studied. Our results show that a YBCO microbridge can intrinsically operate as a photodetector at rates exceeding 100 Gb/s, making it useful as an optical-to-electrical transducer for optoelectronic interfaces in YBCO digital electronics. Simultaneously, YBCO mixers, based on hot-electron effects, should exhibit an intrinsic bandwidth exceeding 100 GHz.

I. INTRODUCTION

TWO CLASSES OF photoresponse—commonly referred to as bolometric and nonequilibrium mechanisms—have been identified in solid-state materials. In the case of the bolometric response, incident radiation raises the temperature of the absorbing medium and results in a measurable change in the absorber’s electrical properties. The speed of the bolometric response is limited by the time required for transferring the excess heat from the absorber to a heat sink, while the transient temperature increase in the absorber and the thermometer sensitivity determine the responsivity. The bolometric mechanism generally gives relatively slow but sensitive detectors [1]. In high-$T_c$ superconducting bolometers, the experimentally observed response has been either transition-edge bolometric or kinetic inductive. In the former, the device is biased at its superconducting resistive transition (in other words, at the critical temperature $T_c$) and becomes a very sensitive thermometer (bolometer) since at $T_c$ the resistance-temperature ($R$-$T$) dependence is very steep. The photoresponse of a superconductor at temperatures far below $T_c$ is due to a change in kinetic inductance. The incident radiation breaks Cooper pairs and reduces the superfluid density, leading to a change in the kinetic inductance $L_{kin}$. In the presence of a bias current, the change in $L_{kin}$ produces a fast voltage transient that is not followed by a slow resistive component [2], [3].

Generally, nonequilibrium processes in solids, and superconductors in particular, give much shorter (as compared to bolometric) photodetector response times. In nonequilibrium detectors, the signal depends on the photogenerated nonequilibrium between the distributions of electronic and lattice excitations. The nonequilibrium conditions can be described using a two-temperature model, in which different temperatures, $T_e$ and $T_{ph}$, are assigned to the electron and phonon subsystems, respectively. Nonequilibrium heating of the electron system in metal films was first described by Anisimov et al. [4] in 1974 and later studied experimentally using an all-optical femtosecond pump-probe technique [5]–[7].

The photoresponse of high-temperature superconducting (HTS) films has been discussed extensively in the literature in recent years. Experiments were usually performed using a pulsed laser source and a high-speed oscilloscope to study the transient, optoelectronic response from a current-biased superconducting microbridge. The relatively high-speed response of simple YBa$_2$Cu$_3$O$_{x-}$ (YBCO) transition-edge bolometers was initially surprising; many authors attributed nanosecond transients to nonequilibrium response mechanisms [8], [9], while only a few claimed that all observations could be explained by equilibrium heating of the whole microbridge [2], [10]. Fast photoresponse transients were also observed in the superconducting state far below $T_c$ and were
interpreted assuming nonequilibrium conditions [3], [11], [12], although an equilibrium mechanism was also suggested [13]. Finally, in some experiments, a nonequilibrium signal was observed to be superimposed on a large and broad bolometric background [14], [15]. We want to stress, however, that in the time domain it is very difficult to distinguish between the nonequilibrium and bolometric responses, simply because an extremely large bandwidth measurement system is required for the nonequilibrium response.

To avoid the aforementioned difficulties in the time-domain measurements, the photoresponse in the frequency domain was studied instead, using a sinusoidally modulated laser source [16], [17]. The bolometric response and its roll-off frequency of ~50 MHz was identified. Simultaneously, a nonequilibrium plateau was shown to extend at 77 K. Finally, pump-probe measurements have demonstrated the existence of an ultrafast (subpicosecond) optical response in HTS materials [19]–[21]. However, a detailed understanding of the energy band structure is necessary to convert the reflectivity data into a time-dependent energy band structure.

Value [5]–[7]. Using sufficiently short pulses, the transient electron energy relaxation times for hot electrons can be studied. A short (usually femtosecond) laser pulse is used to induce nonequilibrium conditions in the tested material, and a second time-delayed pulse is used to measure the induced change in either reflectance or transmittance of the sample. The electron and phonon temperatures are related to the change in reflectivity in several ways. One widely used technique is to probe the smearing of the hot-electron distribution at the Fermi surface by using photon energies close to the Fermi-level value [5]–[7]. Using sufficiently short pulses, the transient energy relaxation times for hot electrons can be studied. Pump-probe measurements have demonstrated the existence of an ultrafast (subpicosecond) optical response in HTS materials [19]–[21]. However, a detailed understanding of the energy band structure is necessary to convert the reflectivity data into a time-dependent $T_c$. For this reason, results from HTS pump-probe experiments remain controversial. They have demonstrated, however, that the standard smearing model is fully applicable in YBCO films with oxygen content above that corresponding to the metal–insulator transition. The Fermi-energy ($E_F$) level depends on the oxygen doping in YBCO and shifts downward (in the hole picture) as the oxygen content decreases. The position of $E_F$ is approximately 2 eV above the $\delta$ bulk band for films with $T_c \approx 60$ K [22]. Finally, pump-probe experiments have also shown that the nonequilibrium photoresponse without a thermal (bolometric) background can be observed in superconducting YBCO only under very-low-fluence conditions [21].

From the point of view of applications, YBCO is ideally suited for digital and communication applications because of its high absorption coefficient in the wavelength range from the ultraviolet to 10 $\mu$m and single-picosecond response. Examples include applications requiring ultrafast infrared photodetectors and mixers as well as very-high-data-rate optical-to-electrical transducers in optoelectronic interfaces for superconducting digital electronics.

In this paper, we report the ultrafast response of a current-biased YBCO microbridge, fabricated from a very-high-quality epitaxial YBCO film. We observed waveforms of two different shapes, depending on whether the microbridge was biased in the superconducting or switched (hot-spot) state. We have obtained conclusive evidence for the existence of nonequilibrium electron heating in YBCO irradiated by femtosecond optical pulses by simultaneously observing both the nonbolometric and bolometric signals. We have also introduced a comprehensive description of a nonequilibrium kinetic inductive model to describe the photoresponse in the superconducting state. Furthermore, we have studied the propagation of picosecond electrical pulses in a YBCO coplanar waveguide (CPW) and were able to connect our results with previous observations. All of our experiments were performed using a cryogenic electrooptic (EO) experimental setup, characterized by <300-fs temporal resolution and <150-$\mu$V voltage sensitivity, which are well below the characteristics of the transients reported here.

II. EXPERIMENTAL METHOD

Our previous investigations of the ultrafast photoresponse in YBCO microbridges showed the presence of a 1.5-ps-wide signal [12], but the large size of the microbridge and the geometrical shape of the entire sample prevented us from drawing conclusions about the intrinsic photoresponse speed. For this work, we designed a sample structure optimized for EO sampling measurements, which at the same time facilitated a relatively simple fabrication technique. The microbridge was made small, in order to be treated as a point source of the photogenerated signal, so its resistance did not have to be matched to the transmission line impedance. Since it is almost impossible to accurately terminate the transmission line for a broad-band signal such as the picosecond electrical pulse, we instead made the transmission line as long as possible. In that way, we achieved an 80-ps-long reflection-free time window for the EO measurements, eliminating from our waveforms the artifacts that may be caused by reflections at the end of the transmission line. To maximize the coupling between the electric field and the EO crystal, we used a CPW transmission line, which is also simple to fabricate in a single-layer YBCO film.

We used high-quality, 100-nm-thick epitaxial YBCO films, grown on 0.5-mm-thick 6 $\times$ 6-mm$^2$ LaAlO$_3$ substrates using pulsed laser deposition. Several test structures were fabricated on each chip using a standard photolithographic technique and wet etching in 0.001-M citric acid. The experimental structure (shown as an inset in Fig. 1) consisted of a 4-mm-long CPW with a 30-$\mu$m-wide center line and 7-$\mu$m-wide gaps to the ground planes. Gold contact pads were deposited in both ends, using ex situ evaporation and lift-off. A 5-$\mu$m-wide 7-$\mu$m-long microbridge was placed in the middle of the CPW center line. Typically, after processing, the bridges exhibited (see Fig. 2) a zero-resistance temperature $T_{c0} > 89$ K, a transition width $<1.5$ K, and a critical current density $j_c > 10^6$ A/cm$^2$ at 77 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 20 K–80 K range and stabilized to ±0.2 K by a temperature controller. One end of the CPW was wirebonded directly to a semirigid, 50-Ω coaxial cable, while the other end was wirebonded to ground on the alumina plate. The 1.2-m-long cable brought the signal out of the dewar and, together with an 18-GHz-bandwidth bias-tee and a 20-GHz-bandwidth amplifier (30-dB gain), allowed us to observe the bolometric part of the bridge response on a 14-GHz-bandwidth oscilloscope.

As shown in the Fig. 1 inset, the entire waveguide structure was overlaid with an EO LiTaO$_3$ crystal to facilitate the EO sampling measurements.

The complete experimental setup is shown in Fig. 1. A commercial Ti:sapphire laser, pumped by an Ar-ion laser, was used to excite picosecond pulses in the microbridge and electrooptically 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 arrangement that allowed us to observe the sample during beam positioning. The average optical power of the 400-nm light, measured at a position just...
outside the dewar, was ~2 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 ~1 mW at the YBCO detector surface, corresponding to a fluence of 17 μJ/cm$^2$. Taking the geometry as well as the reflectance and transmittance of YBCO into account, we estimate the power actually absorbed by the microbridge to be only ~60 μW (fluence 1 μJ/cm$^2$). According to previous experiments [12], the permanent temperature increase due to laser illumination was ~3 K/mW. Thus, the temperature of the bridge increased only ~0.2 K in our case.

The second (sampling) beam (see Fig. 1) traveled through a computer-controlled delay line with 1-μm resolution and 180-mm total travel, corresponding to a time delay resolution of <6 fs and a maximum time window of 1200 ps. The beam had ~20-mW average power outside the dewar and was focused to a ~10-μm-diameter spot at the gap between the CPW center line and ground plane, only ~20 μm from the microbridge where the photoresponse signal was generated. The bottom face of the LiTaO$_3$ crystal had a dielectric wavelength-selective high-reflectivity (HR) coating, which reflected the 800-nm-wavelength sampling beam but allowed the frequency-doubled excitation beam to pass through. The reflected sampling beam had ~2-mW average power and was directed to an analyzer section. The electric field of the propagating pulse, which is parallel to a LiTaO$_3$ crystal axis, induces extra birefringence in the crystal. In the analyzer section, the polarization change due to the birefringence is converted into an intensity change that is measured differentially. The electric-field sensitivity was maximized and linearized by choosing the polarization of the incident sampling beam to a 45° angle with the LiTaO$_3$ crystal axis and by adjusting the compensator, which is placed in the sampling-beam path before the analyzer.

In the electronic part of the experimental setup (Fig. 1), mixers allow for the use of high-frequency modulation (higher than frequencies where the $1/f$ noise of the laser dominates) and the measurement of the differential signal by a lock-in amplifier. The computer records the time-domain evolution of the electric field at the sampling point by moving the delay stage and measuring the lock-in amplifier output. In the measurements presented here, averaging of up to 50 traces was used to increase the signal-to-noise ratio (SNR). By introducing a known voltage on the CPW and measuring the resulting sampling beam intensity change, the system can be calibrated so the computer directly calculates and displays the measured signal magnitude in millivolts. From a practical point of view, the EO sampler can be regarded as an ultrafast (<300-fs temporal resolution) and ultrasensitive (<150-μV voltage sensitivity) sampling oscilloscope. The temporal resolution and field sensitivity have been verified by measurements on a GaAs photoconductive switch [23] and characterization of single-flux-quantum pulses [24].

During the measurements, the microbridge was biased through the bias-tee using a voltage source. Current–voltage ($I$–$V$) characteristics measured in a four-point configuration at different temperatures are shown in Fig. 3. The curves are typical for a superconducting YBCO microbridge [25]. One can clearly distinguish the two different voltage states—the superconducting/flux-flow state with zero/low voltage across the bridge and the switched state where the current is almost constant while the voltage across the bridge increases as the bias is increased. To be able to bias the microbridge in the switched state, it is crucial to use a voltage source, and not a current source. The switched state, where the microbridge is resistive, is caused by the formation of a hot spot in the bridge.

As the bias current through the bridge is increased, entering the flux-flow regime, the bridge becomes lossy and dissipates heat. When the generated heat is more than the surrounding cryogen can dissipate, a hot spot forms in the microbridge and it switches to a state with lower current and higher voltage. In the hot spot, the temperature is roughly constant,
equal to $T_c^2/T_b$, where $T_b$ is the bath temperature [25]. If the microbridge is long, the hot spot initially covers only part of the bridge, giving rise to a constant-current (plateau) region as the hot-spot size increases. For fairly small microbridges, the hot spot instantly covers a very large portion (or all) of the bridge and the current plateau is quite small (see, e.g., the 80-K curve in Fig. 3). When the entire bridge is driven normal, we observe the normal-resistance, linear behavior of the $I$–$V$ characteristics. Since our microbridge is only 7-$\mu$m long and we set the switched state bias point at the upper end of the plateau, we assume that the entire length of our bridge is driven into the normal state with a uniform hot-spot temperature.

III. Results

A. Switched-State Photoresponse

Fig. 4 shows a typical transient, measured when the bridge was biased in the switched state. The main figure displays the single-spike response with a low-noise baseline, indicating the absence of reflections and other artifacts caused by the measurement technique. The inset shows the same pulse at a higher time resolution. We note that it has a near-Gaussian shape and that the measured 1.1-ps-wide response is not limited by the resolution (<300 fs) of our EO sampler. The trace shown in Fig. 4 was acquired at $T_b = 50$ K, but essentially the same waveforms with full-widths at half-maximum ranging from 1.1 to 1.3 ps were observed at all tested temperatures in the 20-K–80-K range. This suggests that the response is not directly related to the hot spot temperature.

After the picosecond transient in Fig. 4, we observed an approximately 200-$\mu$V-level plateau (on the 1-ps/div time scale) associated with the slow bolometric response. The picosecond transient is superimposed on this very slow tail, which we simultaneously observed (not shown) on a 14-GHz-bandwidth oscilloscope. The bolometric response had $\sim$250-$\mu$V amplitude and a nanosecond fall time, shorter than the repetition rate of our Ti:sapphire laser. The oscilloscope signal was used to optimize the alignment of the excitation beam for maximum response.

B. Superconducting-State Photoresponse

When the bridge was biased in the superconducting state, we observed a $\sim$1-ps-wide transient of the shape shown in Fig. 5. No signal could be seen on the oscilloscope in this case. We note that the waveform is markedly different from that measured in the switched state (presented in Fig. 4) and consists of a large positive component, immediately followed by a negative part. This bipolar signal is characteristic for the kinetic inductive response [3], [13]. Nearly identical transients were observed for all different bias currents in the superconducting state in the entire temperature range from 20 K to 80 K. After the main transient, a small oscillatory signal can be observed. These trailing oscillations were present in all traces, but their origin is not understood at this point. The period of these oscillations does not correspond to any feature size, as it would if transient reflections were the cause.

C. Effects of Pulse Propagation

Fig. 6 shows the superconducting-state photoresponse pulse measured at two different positions on the CPW. The top trace was measured only 20-$\mu$m from the microbridge, as were all other transients reported here. At this distance, the distortion due to propagation can be considered negligible. The bottom trace was measured in the same experiment and under the same conditions except that the sampling spot had been moved 600-$\mu$m down the transmission line. We note that the propagated pulse shape is qualitatively very similar to the waveforms we
measured in our earlier experiments [12], where the sampling point was more than 0.5 mm away from the bridge. After propagation, the pulse has clearly suffered some distortion, showing how critical it is to sample the signal as close as possible to the generation point in order to extract the intrinsic response. From the temporal displacement (see time scale in Fig. 6) we calculated the propagation speed of our pulse to be $6.9 \times 10^7$ m/s, corresponding to an effective CPW dielectric constant $\varepsilon_r = 19$. This value is almost twice the quasi-static ($\varepsilon_{\text{LAO}} + \varepsilon_{\text{He}})/2$ value for the YBCO/LaAlO$_3$ CPW ($\varepsilon_{\text{LAO}} \approx 20$) with a helium gas superstrate ($\varepsilon_{\text{He}} \approx 1$), showing directly the influence of the LiTaO$_3$ sampling crystal ($\varepsilon_{\text{ITO}} \approx 42$). On the other hand, $\varepsilon_{\text{eff}}$ is below the $(\varepsilon_{\text{LAO}} + \varepsilon_{\text{ITO}})/2$ value since the LiTaO$_3$ is separated from the CPW by an $\approx 1$-$\mu$m-thick reflective coating and an inevitable He-filled gap between the crystal and the YBCO/LaAlO$_3$ structure. We associate the observed amplitude attenuation of the signal in Fig. 6 with losses occurring in the LiTaO$_3$ HR coating rather than in the YBCO waveguide.

### IV. Modeling

The fast photoresponse of HTS materials has been extensively studied at the theoretical level, using either the nonequilibrium electron-heating [16], [26] or the kinetic-inductance [2], [3] models to explain the observed electrical transients. The measured signals were, however, attributed to one or the other model, and few attempts were made to reconcile the two approaches [27].

#### A. Nonequilibrium Electron Heating

A two-temperature model has previously been used to describe nonequilibrium conditions in superconductors [16], [26]. In the model, the electron and phonon subsystems are assigned temperatures $T_e$ and $T_{\text{ph}}$, respectively. The temperature is used as a measure of the average energy in each system, and the term “nonequilibrium” refers to the conditions under which the two systems have different temperatures. The balance between the systems is governed by the coupled differential equations:

$$
\frac{d\theta_e}{dt} = \frac{\alpha P_0(t)}{V} - \frac{C_e}{\tau_{e-\text{ph}}} (T_e - T_{\text{ph}})
$$
$$
\frac{d\theta_{\text{ph}}}{dt} = \frac{C_{\text{ph}}}{\tau_{e-\text{ph}}} (T_e - T_{\text{ph}}) - \frac{C_{\text{ph}}}{\tau_{\text{es}}} (T_{\text{ph}} - T_s)
$$

where $C_e$ and $C_{\text{ph}}$ are the electron and phonon specific heats, $\alpha$ is the radiation absorption coefficient, $V$ is the volume of the bridge, and $T_s$ is the sample temperature. $P_0(t)$ is the incident optical power, in our case modeled as a Gaussian-shaped pulse. The equations also contain the characteristic times $\tau_{e-\text{ph}}$ for electron-phonon relaxation, and $\tau_{\text{es}}$ for phonon escape to the substrate.

The time dependence of $T_e$ and $T_{\text{ph}}$, resulting from numerically solving (1) is shown in Fig. 7. In calculations, we used the temperature dependence of the electron specific heat, $C_e = \gamma T_e$ and values for $\gamma$ and $C_{\text{ph}}$ from [28], [29]. Since the film thickness is roughly equal to the light-penetration depth and the spot size is larger than the bridge size, we assume that the radiation is uniformly absorbed. $T_s$ is equal to the hot-spot temperature $T_{\text{ph}}$ $T_e / T_{\text{ph}}$. The simulated waveform is in units of $T_e$, but it can be easily translated into voltage, which is proportional to $\Delta T_e$, according to $\Delta V = I(dR/dT)\Delta T_e$, where $I$ is the bias current and $R$ is the bridge resistance. The rise time of $T_e$ is determined by either the laser-pulse rise time or the electron thermalization time $\tau_{e-\text{th}}$, whichever is slowest. The fall time is governed by $\tau_{\text{es}}$. The electron–electron scattering time $\tau_{e-\text{es}}$ is generally considered very short, typically 100 fs or less, so the thermalization of the electron subsystem has usually been assumed to be an almost instantaneous process [30]. In our case, this would mean that the rise time of the transient should follow the laser pulse ($\approx 100$ fs). This is clearly not the case; instead, we observe a rise time of 0.7 ps. This leads us to the
conclusion that $\tau_{et}$ is substantially longer than $\tau_{ee}$. It has been recently demonstrated for electrons in gold films [31], [32] that the scattering time depends on the degree of excitation and only very highly excited electrons have femtosecond scattering times. As the electrons cool down, the scattering time increases. In our case, the energy of each of the $\sim 10^5$ incident 3-eV photons is sufficient for breaking an equivalent of at least 100 Cooper pairs, creating a very broad-band initial distribution of excited electrons. Furthermore, $T_e$ is a macroscopic quantity. The electron subsystem cannot be assigned a temperature until it has regained a Fermi–Dirac-like distribution, which, in turn, cannot be achieved after one scattering event; instead, a very large number of events with different initial electron energies must be expected [30]. In our simulations, we have taken this into account by assuming that the electron system responds to the incident optical pulse with a broadened Gaussian shape.

B. Nonequilibrium Kinetic Inductance

According to kinetic inductance theory [2], a photoinduced change in the Cooper-pair density gives rise to a voltage transient

$$V_{\text{kin}} = I \frac{dL_{\text{kin}}}{dt}.$$  \hspace{1cm} (2)

In previous photoresponse experiments, the kinetic inductance has been used to explain the measured transients, but it was assumed that the change in the Cooper-pair density was associated with a uniform temperature rise of the entire bridge. However, in previous experiments the negative part of the transient has been small and relatively slow [3]. We believe these observations were affected by the pulse distortion due to propagation on the transmission line before the electronic read-out system was reached, as clearly seen in Fig. 6. In the measurements presented here (Fig. 5), the negative component is almost as fast as the positive one. Such a rapid cooling of the bridge itself is not possible due to the limited speed of processes involving phonon escape out of the film. Instead, we believe that the same nonequilibrium conditions can be held accountable for the $L_{\text{kin}}$ change. We state that the superfluid fraction is not related to $T_e$, but $T_e$ according to the formula [13]

$$f_{sc} = 1 - \left( \frac{T_e}{T_c} \right)^2.$$  \hspace{1cm} (3)

This allows us to calculate the kinetic inductance as

$$L_{\text{kin}} = \frac{1}{\varepsilon_0 \omega_p^2} \frac{1}{f_{sc}} \frac{l}{wL}.$$  \hspace{1cm} (4)

where $\varepsilon_0$ is the vacuum permittivity, $\omega_p = 1.67 \times 10^{15}$ s$^{-1}$ is the plasma frequency of YBCO, and $L$, $w$, and $d$ are the bridge length, width, and film thickness, respectively. We note that $T_e$ couples (1) and (3).

Fig. 8 illustrates the nonequilibrium kinetic inductance model [solutions of (1)–(4)], starting with the excitation laser pulse in the top graph. The second graph shows the resulting electron and phonon temperatures, after the excitation pulse has been broadened by the finite response time of the electron system, and $T_s$ was set equal to $T_b$. The next two graphs in Fig. 8 show the superfluid fraction calculated from (3) and the kinetic inductance calculated from (4). Finally, the last graph shows the voltage signal calculated as the derivative of $L_{\text{kin}}$ multiplied by the bias current, in accordance with (2). The similarity between this trace and our waveforms observed in the superconducting state (see, e.g., Fig. 5) is apparent.

V. DISCUSSION

A. Switched-State Photoresponse

Fig. 9 shows an experimentally obtained waveform (dots), essentially identical to that presented in Fig. 4, but acquired at $T_b = 80$ K, which corresponds to a hot-spot temperature of 99 K. The solid line represents the result of our simulations based on the photoinduced nonequilibrium heating of the electron subsystem model, discussed in Section IV-A. A least-square fit to the rising edge of the transient rendered $\tau_{et} = 0.56$ ps. Similarly, we adjusted the parameter $\tau_{e-ph}$ to get a least-square fit to the falling edge of the transient and obtained the value $1.1$ ps for $\tau_{e-ph}$. We interpret $\tau_{et} = 0.56$ ps and $\tau_{e-ph} = 1.1$
ps as the intrinsic values for characteristic relaxation times of electrons in YBCO at 99 K excited by 3-eV photons.

The bolometric component, simultaneously observed on the oscilloscope, had a few-ns fall time, consistent with the phonon escape time $\tau_{\text{es}}$ [2]. The amplitude ratio between the fast transient and the bolometric response is directly related to the ratio between $C_e$ and $C_{\text{ph}}$. Since we have simultaneously measured both the electron and lattice responses, we were able to determine, by comparing with the electron-heating model, the ratio $C_{\text{ph}}/C_e$ at 99 K to be 38.

B. Superconducting-State Photoresponse

Fig. 10 shows a waveform (dots) acquired in the superconducting state at $T_b = 60$ K. The solid line is a fit to the waveform and was obtained by solving simultaneously (1)–(4) (see Fig. 8), with $\tau_{\text{et}}$ as an adjustable parameter (as in the case of the switched state). From this simulation, by using a least-square fit to the positive part of the transient, $\tau_{\text{et}}$ was found to be $0.9 \pm 0.1$ ps in the entire tested temperature range (20 K–80 K). We note that in the superconducting state, $\tau_{\text{et}}$ does not depend strongly on temperature and is considerably longer than $\tau_{\text{et}} = 0.56$ ps found in the switched state.

In principle, we could also determine $\tau_{\text{et}}$ by fitting the negative part, but due to the influence of the trailing oscillations, any values found would have a large error. Thus, for self-consistency reasons, we used, with good results, the value $\tau_{\text{et}} = 1.1$ ps, obtained at 99 K from Fig. 9 (switched-state fitting). The validity of the kinetic inductance mechanism was further verified by investigating the dependence of the photoresponse amplitude on bias current. Fig. 11 shows linear dependencies, obtained using two different optical power levels, in complete agreement with (2).

VI. CONCLUSION AND OUTLOOK

We have demonstrated that electrical transients of single-ps duration can be generated by a YBCO microbridge biased in either the switched or superconducting state. Nonequilibrium conditions govern the observed photoresponse and can be explained with the help of a nonequilibrium electron-heating model. In either case, the origin is the transient increase of electron temperature. In the superconducting state, pair-breaking followed by fast quasi-particle recombi-
nation leads to a rapid change of superfluid density, which in the presence of a bias current gives rise to an oscillatory transient due to kinetic inductance. In the switched state, the microbridge is resistive and the resistance of the bridge increases due to the raised electron temperature, so a bias current produces a voltage spike. From our experiments we were able to extract the characteristic time constants $\tau_{\text{on}} = 0.56 \text{ ps}$ and $\tau_{\text{off}} = 1.1 \text{ ps}$ in the switched state, and $\tau_{\text{on}} = 0.9 \pm 0.1 \text{ ps}$ in the superconducting state, which must be regarded as the intrinsic speed limitations for YBCO hot-electron photodetectors and mixers. The mechanism for the photoresponse is spectrally very broadband and detection from ultraviolet to-10-$\mu$m wavelengths has been experimentally demonstrated [34], [35]. Furthermore, the biasing requirements are very simple, and the ratio between the ultrafast electronic response and the thermal response was found to be approximately 20:1 at 80 K, practically eliminating the risk of thermal runway (the average, laser-induced heating of our microbridge was found to be only $\sim 0.2 \text{ K}$).

Our studies show the high-speed capabilities of YBCO photodetectors, opening the door to many interesting applications in the area of superconducting optoelectronics. The measured time constants demonstrate that such photodetectors (assuming perfect heat sinking) can operate in digital applications requiring data rates far exceeding 100 Gb/s, while mixers can reach an IF bandwidth greater than 100 GHz. Fiberoptic communication receivers with Gb/s rates are an attractive possibility, especially if the operating wavelength is shifted to-infrared communications or</p>
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John S. Preston, photograph and biography not available at the time of publication.

Frank A. Hegmann, photograph and biography not available at the time of publication.