Ultrafast linear kinetic inductive photoresponse of YBa$_2$Cu$_3$O$_{7-\delta}$ meander-line structures by photoimpedance measurements

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We report the experimental demonstration of the linear kinetic-inductive photoresponse of thin-film YBa$_2$Cu$_3$O$_{7-\delta}$ meander line structures, where the photoresponse amplitude, full-width-half-maximum, and rise time are bilinear in the incident optical power and bias current. This bilinear behavior reveals a trade-off between obtaining high responsivity and high speed photodetection. We also report a rise time as short as 29 ps in our photoimpedance measurements. © *2011 American Institute of Physics*. [doi:10.1063/1.3561742]

The interaction of light with superconducting samples is long known to perturb superconductivity,[1–4] which can be used as a probing mechanism for optoelectronic applications.[5–13] In general, photons of energy greater than the Cooper pair binding energy (2Δ) can initiate a chain of pair breaking events resulting in a deviation of the quasiparticle and pair densities from their equilibrium values. Typically, these distributions depend on temperature, optical power and wavelength, thermal boundary conditions, and material properties such as electron–electron and electron–phonon interactions times, electron density, coherence length, penetration depth, and geometry.[6,14] While determining the spatial and temporal distribution of quasiparticles and pairs under a time-varying optical illumination is a profound problem in nonequilibrium superconductivity, many of the important concepts of such an interaction for device applications can be captured by means of a much simpler and more phenomenological approach, namely, the kinetic inductance model.[13] Within the kinetic inductance model, the presence of the superconductive condensate, at a macroscopic level, can be adequately modeled by an additional inductive channel for charge transport. The optically initiated pair breaking mechanism, within this framework, should be interpreted as the spatial and temporal variations in the kinetic inductance and the normal resistance of the superconducting specimen.

Many researchers have experimentally studied the kinetic inductive photoresponse of superconducting thin films through photoimpedance measurements.[6,15] In photoimpedance measurements, light induced changes in the microwave impedance of the superconducting structure are measured by an external high-frequency circuit. In its simplest form, the specimen is externally biased with a dc current and connected to a fast oscilloscope in series with a high bandwidth amplifier; absorption of optical photons then changes the impedance of the sample and produces a transient voltage response. A number of previous works have reported photoimpedance measurements on different superconductors mainly concluding that: (1) the resistive photoresponse dominates at temperatures well below the critical temperature (T_c), whereas the kinetic inductive response becomes the main mechanism of photoresponse close to T_c. (2) In the kinetic inductive regime the photoresponse could be very fast, with a rise time as low as 50 ps, and is mainly limited by the time constants of the peripheral measuring apparatus. (3) The dependence of the photoresponse amplitude varies nonlinearly with the incident optical power.

The nonlinearity of the kinetic inductive photoresponse intrinsically arises from the nonlinear dependence of the kinetic inductance of a superconducting sample on the Cooper pair density. Therefore, even though changes in the Cooper pair density, under certain conditions, may vary linearly with the incident optical power, the resultant variation in the kinetic inductance is generally nonlinear. This point can be readily observed for a thin-film sample[16]

$$L_k = \frac{m^*\ell}{n^*(q^*)^2 A},\qquad(1)$$

where L_k is the kinetic inductance, ℓ and A are the length and the cross section area of the sample, m^* and q^*, respectively, are the mass and charge of a Cooper pair, and n^* is the density of Cooper pairs. Accordingly, the kinetic inductive photoresponse approximately reads[7]

$$V_{ph} = \frac{d}{dt}(L_k I_0),\qquad(2)$$

where I_0 is the bias current. Nevertheless, we have theoretically shown elsewhere[17,18] that if the optical power and the bias current are far from their critical values, and the temperature is not too close to T_c the kinetic inductive response can be linearized giving a frequency-dependent voltage responsivity

$$R_v(\omega) \equiv \frac{V_{ph}(\omega)}{P_o(\omega)} = \left(\frac{\eta_Q \tau_Q I_0}{2\Delta A \ell n^*}\right)\left(\frac{j\omega L_{k0}R_{n0}}{j\omega L_{k0}+R_{n0}}\right),\qquad(3)$$

where P_o and ω are the incident optical power and modulation frequency, η_Q is the pair breaking efficiency, τ_Q is the Cooper pairs recombination life time, and R_{n0} and L_{k0} are the equilibrium normal resistance and kinetic inductance of the sample in the absence of illumination. This regime of operation is particularly useful for optoelectronic device applica-

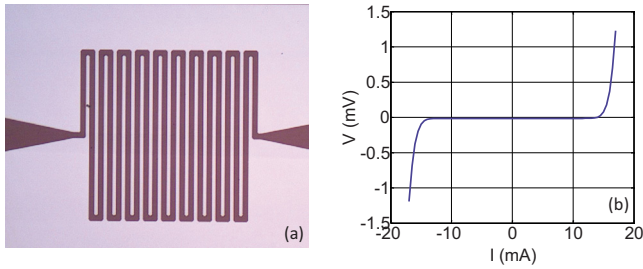a)Author to whom correspondence should be addressed. Electronic mail: haatikia@maxwell.uwaterloo.ca.

FIG. 1. (Color online) (a) Image of the 5 μm meander line. (b) Measured current-voltage characteristics of the 5 μm meander line at 77 K.

FIG. 3. (Color online) Photoresponse waveforms for the 5 μm meander line under 1.6 mW of incident optical power with a varying bias at 77 K and 28 dB amplification. (Inset) Photoresponse waveform under 1.2 mW of incident optical power and 7.5 mA bias current with a 29 ps rise time.

tions such as photodetectors and optically tunable microwave-photonic devices such as delay lines, resonators, and filters where linear tunability is highly desirable.[19]

To serve as a detecting element, we have used a 100 nm thick YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) thin-film (THEVA, Ismaning, Germany) meander line structure with 5 μm line widths and slots, covering an area of 176 μm $\times$ 200 μm. The meander line structure is placed at the midpoint of the center strip of a 50 GHz bandwidth 50 Ω superconducting coplanar waveguide (CPW) transmission line. Figure 1 shows the image of the meander line and the current-voltage characteristics at 77 K. The critical current is found to be 13 mA, and the bias current is selected to be below this value. The meander line is externally dc biased through high bandwidth bias-tees. One end of the CPW is terminated with a 50 Ω load to suppress any reflected signals. The other end is connected to a high bandwidth microwave amplifier with a gain of 28 dB, followed by a fast oscilloscope where the response to a train of 1550 nm wavelength, 45 ps wide Gaussian optical pulses is measured. A block diagram of the measurement setup is shown in Fig. 2. More details in regards to the photoimpedance experimental setup can be found in Ref. 20.

Figure 3 illustrates typical photoresponse waveforms for different bias currents at an incident optical power of 1.6 mW. The inset of Fig. 3 illustrates an operating point, where we have measured rise times as short as 29 ps. Figure 4(a) shows that the photoresponse amplitudes of the detector, for fixed bias currents, varies linearly with the incident optical power. Moreover, Fig. 4(b) demonstrates that the responsivity of the device has a linear dependence on the bias current. These two observations confirm our previous theoretical pre-
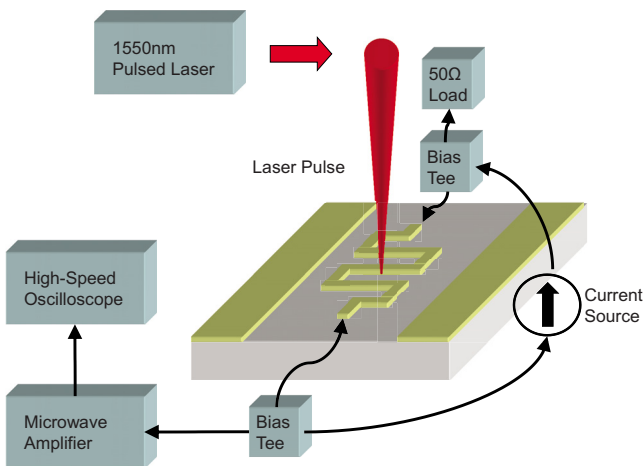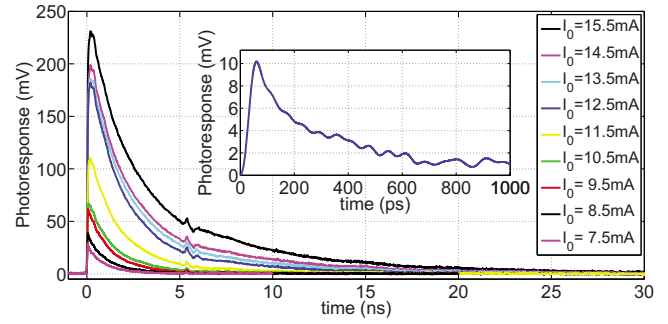
diction of the linear kinetic inductive response represented by Eq. (3). This linear response sustains as long as the perturbation in both kinetic inductance and normal resistance is small. This also implies that the fractional change in both the Cooper pair density and quasiparticles is small. These values, in general, depend on temperature, bias current, and average incident optical power. The linear regime of operation for this device, at a given temperature, is clearly illustrated by the range of current and optical power values in Fig. 4.

The full-width-half-maximum (FWHM) of the photoresponse is a measure of the photoinduced disturbance in the detector, which according to Eq. (2) equals to ($\delta L_k I_0$). The perturbation in the kinetic inductance, δL_k, in the linear kinetic inductive regime, linearly varies with optical power and is independent of the bias current.[18] Thus, the ($\delta L_k I_0$) product, and consequently, the FWHM, should be bilinear in the optical power and bias current which is clearly shown by Fig. 5. This point readily reveals the trade-off between obtaining high responsivity and short photoresponse waveforms in linear kinetic inductive detectors, because the former requires a higher bias current whereas the latter demands a small bias current.

In addition to amplitude and FWHM, the rise time of the photoresponse waveform is also bilinear in optical power and bias current, as illustrated by Fig. 6. In terms of an electrical circuit model, the detector acts like an RL circuit with time varying R and L and a constant total current I_0.[18] In this scenario, the rise time depends on the ($\delta L_k I_0$), which was shown to be bilinear in current and optical power. This point once again manifests itself as a trade-off between speed and responsivity in the linear regime. A set of similar results was obtained for a meander line with 3 μm line and slot widths,

FIG. 2. (Color online) Block diagram of the photoimpedance measurement setup of the meander line structure.
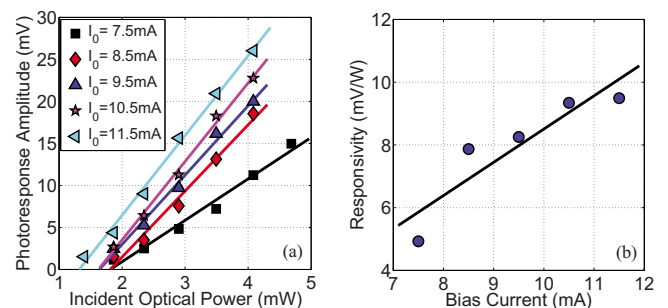

FIG. 4. (Color online) (a) Photoresponse amplitude vs incident optical power with a varying bias current. (b) Responsivity vs bias current.
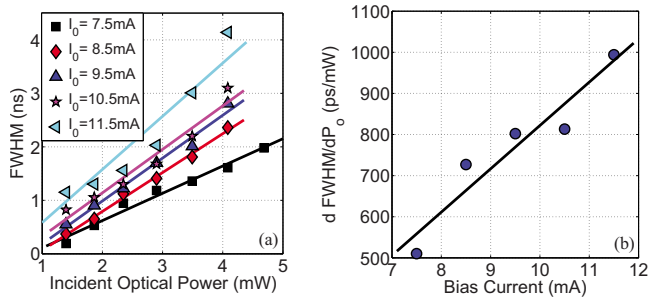
FIG. 5. (Color online) (a) FWHM of the photoresponse waveform vs incident optical power with varying bias current. (b) The slope of the changes in FWHM with optical power as a function of bias current.

for which the same trends as the presented device was observed.

In conclusion, we have characterized the linear kinetic inductive photoresponse of thin-film YBCO meander line structures, where the photoresponse amplitude, FWHM, and rise time of the waveforms are bilinear in optical power and bias current. For a given operating point, we have been able
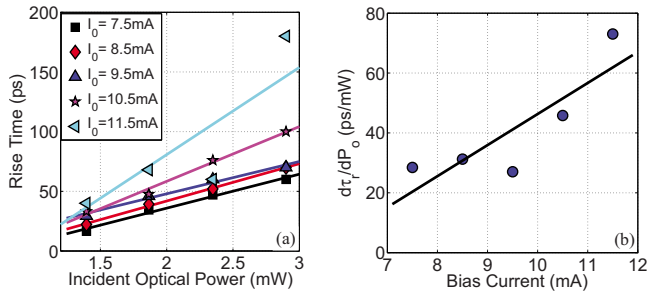

FIG. 6. (Color online) (a) Rise-time vs incident optical power with varying bias currents. (b) The slope of the changes in rise time with optical power as a function of bias current.

to measure a short 29 ps rise time in the linear kinetic inductive regime.

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