Optical-Microwave Interaction Modeling in High-Temperature Superconducting Films

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***Abstract*—Optical-microwave interaction in high-T_c superconductors is investigated for performing basic optoelectronic functions in cryogenic environment. A fast bolometric photoresponse in conjunction with the unique electrical properties of high-temperature superconductor (HTS) materials allows us to explore a series of novel optoelectronic devices with low-noise/low-power and high-speed/high-frequency characteristics. After reviewing the HTS photoresponse categories, we describe the fast bolometric photoresponse and its condition with heat transfer analysis. The analytical solution of heat diffusion equation for an HTS strip mounted on a substrate will be presented for three different type of optical sources. Then the effect of optical irradiation will be incorporated in the two-fluid model by thermomodulation concept in order to model the interaction of optical radiation with electrical signal. The current-field relationship and the supercurrent response time are evaluated in the presence of both optical and electrical signals. Our numerical simulations for YBaCuO film will demonstrate the possibility of RF harmonic generation when the laser beam is modulated by the RF signal in the presence of dc bias current and RF signal mixing when the HTS film is fed by a time–harmonic microwave source. The developed model can also be used to study optical control and tunability techniques for HTS microwave devices for analog signal processing.**

***Index Terms*—High-temperature superconductors, microwave-photonics, superconducting films, superconducting microwave devices, superconducting optoelectronics.**

I. Introduction

RECENT developments in photonic technology and superconducting electronics is opening a window of opportunity for *superconducting optoelectronics* [1]. This term refers to electronic functions performed by optical irradiation via the photoabsorption effect in high-T_c superconductors in cryogenic environment. The unique combination of high electrical conductivity and ultrafast photoresponse in high-T_c superconductors opens a new possibility for a physical interaction to permit coupling between the electrical and optical domains. Photonics can be utilized for performing basic optoelectronic functions such as generation, detection, processing and control of high frequency electronic signals in high-temperature superconductor (HTS) media. The photoabsorption phenomenon in HTS materials provides an opportunity for a novel class of optoelectronic devices as well as a new technique for optical control of superconducting microwave devices, somewhat like a photoconductivity effect in semiconductors [2]. These devices extend from integrated optoelectronic and optically tuned microwave devices to high current fast switches for power applications [3], [4]. Since the superconducting optoelectronic devices are intended to operate at cryogenic environment, it is expected that they would exhibit low-noise/low-power and high-speed/high-frequency characteristics.

The purpose of this paper is to introduce a theoretical framework for dealing with optical-microwave interaction in HTS media for optoelectronic applications. First, we consider the HTS photoabsorption phenomenon as a key mechanism of optical-electrical interaction and review different types of HTS photoresponse. Based on theoretical considerations and experimental observations, the optical-microwave interaction will be investigated via the fast bolometric photoresponse in the HTS films under a certain conditions. A thermal analysis will be presented for various optical radiation sources and their analytical discussion will be introduced. The photoexcited HTS film will be then analyzed in the presence of electrical signals in a linear regime, when the applied signal does not impose any nonlinearity in the HTS film. The two-fluid model helps us to simply analyze the behavior of photoexcited HTS film, while the microwave signal is passing through it. The combined thermal analysis and the two-fluid model could be used for investigating the optical-microwave interaction in HTS films, since the temperature shift produced by the optical irradiation causes the variation of superconducting electrical parameters. Finally, numerical simulation based on the experimental data, presents a series of interesting results for performing many optoelectronic functions in HTS films such as photodetection, RF harmonic generation and RF signal mixing.

II. Photoresponse in High-T_c Superconducting Films

Superconductivity is purely quantum and thermodynamical phenomenon. As the temperature of a material drops below its critical temperature T_c the material undergoes a second phase thermodynamical transition and becomes a superconductor. According to the well-known BCS theory [5], in the superconducting state, normal electrons with opposite spins and momenta form pairs, so called Cooper pairs. This pairing mechanism is due to the formation of an energy gap $\Delta(T)$ in the electron density of states, which is temperature dependent. Cooper pairs are bound together with an energy $2\Delta(T)$. The energy gap for most superconductors especially HTS materials falls within a range corresponding to the infrared region. Thus, by applying photons with energy $h\nu \geq 2\Delta(T)$ the Cooper pairs can be broken and the electrons excited to the normal state, as shown in Fig. 1. The way in which the photoexcited electron

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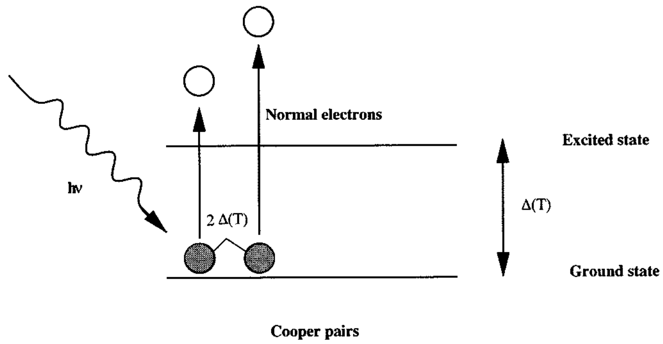


Fig. 1. Photoabsorption phenomenon in HTS materials.

energy gets distributed and subsequently dissipated within the superconductors identify the photoresponse mechanisms. Generally, the HTS photoresponse has been categorized into bolometric and nonbolometric (nonequilibrium) mechanisms. When the optical radiation is applied in the time scale greater than the electron–phonon relaxation time, the bolometric response will be manifested. This results that the photoexcited electrons to reach thermodynamical equilibrium with the phonons, and both electron and phonon subsystems are described by the same temperature shift [6]. Normally, the speed of the bolometric response is limited by the time required for transferring the excess heat from the photoexcited region to a heat sink, so-called phonon escape time $\tau_{\rm es}$ [7] and the hot electron out-diffusion process [8]. Depending on the material, geometry and thickness of the HTS film and its substrate as a heat sink, and the characteristics of the laser source, the speed of the bolometric response may vary from milliseconds to a few nanoseconds [9].

In the nonbolometric regime the quantum response of the electron and phonon subsystems are manifested. Generally, the photon stream is applied in a very short time scale in a form of pulsed radiation. The optical pulse duration is smaller than the electron–phonon relaxation time, so the photoexcited electrons do not have any chance to reach equilibrium with phonons. In the nonbolometric response the electron subsystem is directly heated up while the phonon subsystem remains in the equilibrium and plays the role of heat sink for electrons. The nonbolometric photoresponse time is quite comparable with the electron–phonon relaxation time and normally occurs in a picosecond time scale. Therefore, this type of response is extensively used for the measurement of the electron–phonon relaxation time and also provides more information about the pairing mechanism in high-T_c superconductors [10].

In both photoresponse mechanisms the photoinduced temperature shift in the HTS film gives rise to an alteration of macroscopic parameters such as the superfluid fraction and subsequently the electrical parameters such as the kinetic inductance. The conduction process for any electrical signal with frequency smaller than a gap frequency $(\nu_g = 2\Delta(T)/h)$ applied to the HTS film, can be controlled via the optical radiation, due to a change in the number of Cooper pairs and normal electrons. Because high-T_c superconducting electronic and microwave devices usually operate below their gap frequency, typically 100 GHz, the optical-microwave signals interaction can be attributed to the fast bolometric photoresponse under certain conditions. This type of response in YBaCuO was reported earlier by Gershenzon *et al.* [11] and studied by many researchers [12]–[14].

III. Thermal Analysis of Bolometric Photoresponse in HTS Films

Consider a thin superconducting film deposited on a dielectric substrate. We assume that this structure is intended to operate at the following:

1) temperature range $0.5T_c \leq T \leq 0.9T_c$;
2) below its critical magnetic field (H_{c1}) or in the Meissner state;
3) well below its critical current I_c;

The above operating conditions assure that the fast bolometric response is contributed to the photoresponse and also the thermophysical parameters of the HTS film do not possess a significant temperature dependence. When the optical radiation is incident on the HTS film, some part of that can penetrate into the film. Unlike the conventional low-T_c superconductors the oxygen-rich HTS materials are a very good light-absorber due to its low plasma frequency associated with the low carrier density [15]. The absorbed photons break the Cooper pairs and form photoexcited normal electrons. As the population of the normal electron is increased the temperature of the HTS film goes up, due to electron–phonon interaction. Then the photoinduced excess heat can be dissipated through the substrate. Macroscopically, the absorbed optical radiation acts as an internal heat source within the optical penetration depth, which creates the heat diffusion in the HTS film/substrate. According to the energy conservation law, the temperature shift $\Delta T(\mathbf{r},\, t)$ can be written as follows [6]:

$$C\,\frac{d}{dt}\,\Delta T(\mathbf{r},t) = K\nabla^2\Delta T(\mathbf{r},t) + \frac{P_a(\mathbf{r},t)}{V} - \frac{C_{\rm ph}}{\tau_{\rm es}}\,\Delta T(\mathbf{r},t) \tag{1}$$

where C and $C_{\rm ph}$ are the heat capacities of the HTS film and phonon at initial temperature in J/m^{3}K, K is the thermal conductivity in W/mK, $P_a(\mathbf{r},\, t)$ is the absorbed optical power in W, V is the volume of photoexcited HTS film, and $\tau_{\rm es}$ is the phonon escape time. Taking into account the reflection and transmission of the normally irradiated optical wave from the HTS film and neglecting the reflection from film-substrate and multiple refraction within the film, the absorbed optical power can be expressed as [13]

$$P_a = P_{\rm in}(1-R)\left[1-\exp\left(-\frac{d}{\delta_o}\right)\right] \tag{2}$$

where $P_{\rm in}$ is the incident optical power, R is the reflection coefficient, δ_o is the optical penetration depth, and d is the HTS film thickness. Normally the optical penetration depth for HTS materials is in the range of nanometers [16]. The phonon escape time indicates the thermal decay time for heat loss out of the

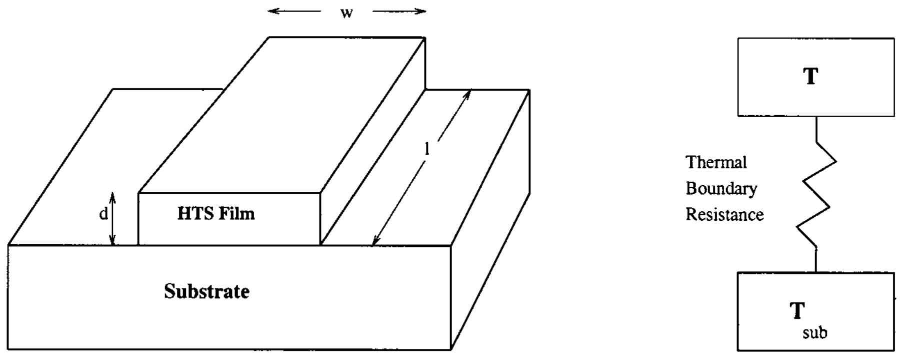


Fig. 2. HTS film on substrate and simplified equivalent thermal model.

photoexcited region through the substrate and is related to the thermal boundary resistance R_{BD} by [17]

$$\tau_{\rm es} = CdR_{BD}. \tag{3}$$

The thermal boundary resistance is expressed in Km^2/W and depends on the dielectric substrate and the geometry of the film-substrate contact. The out-diffusion of hot electrons becomes important when the length of photoexcited region, $l < \sqrt{12D\tau_{e-ph}}$, where D is the diffusion constant [18]. The photoexcited HTS film structure and its equivalent thermal model are depicted in Fig. 2 [19]. In order to increase the speed of bolometric response, it is important to reduce the thickness of the film and most importantly the boundary resistance. It is suggested to use the film thickness comparable to the optical penetration depth in the order of nanometer to reduce the heat diffusion effect in the substrate. Also, a narrow strip contact geometry and a deposition of deoxygenated superconducting layer on the substrate has been demonstrated to effectively reduce the boundary resistance problem [7]. In its more complicated form, a comprehensive thermal models should be applied for the HTS film and substrate structure for more accurate result [20].

Here the emphasis will be placed on the solution of (1), when the heat capacities of the film and phonon remain constant during the optical stimulation and the HTS film is illuminated uniformly. In this case the first term of the right hand side is zero and the absorbed optical power and the temperature shift would be a function of time. We will discuss the temperature shift upon three different optical sources namely continuous, time–harmonic and pulsed laser irradiation.

A. Continuous Optical Irradiation

We wish to find the temporal evolution of the temperature shift of the HTS film when a continuous power P_a is absorbed within the optical penetration depth after $t = 0$. Solution of (1) with boundary condition $\Delta T(0) = 0$ is

$$\Delta T(t) = \frac{P_a \tau_{\rm es}}{C_{\rm ph} V}\left(1 - \exp\left(-\frac{C_{\rm ph}}{C\tau_{\rm es}}\,t\right)\right). \tag{4}$$

Total temperature is then

$$T(t) = T_o + \Delta T(t) \tag{5}$$

where T_o is the initial temperature of the HTS film.

The thermal time constant of the bolometric response is $\tau_{th} = C\tau_{\rm es}/C_{\rm ph}$ which determines the speed of photoresponse. In the steady state regime, the reduced temperature T/T_c can be given by

$$\frac{T}{T_c} = \frac{T_o}{T_c} + \left(1 - \frac{T_o}{T_c}\right)\frac{P_a}{P_c} \tag{6}$$

where

$$P_c = \frac{C_{\rm ph} V T_c}{\tau_{\rm es}}\left(1 - \frac{T_o}{T_c}\right)$$

is the critical absorbed optical power. This quantity indicates the absorbed optical power required for destruction of superconductivity, when all Cooper pairs are broken by the absorbed photons. Equation (6) was experimentally confirmed for YBaCuO thin film [21].

B. Time–Harmonic Optical Irradiation

Consider a continuous wave (CW) laser source, when the optical signal is modulated by a time–harmonic microwave signal with frequency f_m. Since the optical frequency ν is greater than the bound energy of the electron pairs, $2\Delta(T)$, modulation frequency should be chosen in such a way that $hf_m \ll 2\Delta(T)$. In this case the absorbed CW optical power can be simply expressed as

$$P_a(t) = P_m(1 + m\sin 2\pi f_m t) \tag{7}$$

where P_m is the maximum optical power absorbed in the HTS film and m is the modulation index. The temperature shift after $t = 0$ would be

$$\begin{aligned}\Delta T(t) = {} & \frac{P_m\tau_{\rm es}}{C_{\rm ph}V}\left(1 - \exp\left(-\frac{C_{\rm ph}}{C\tau_{\rm es}}\,t\right)\right) \\ & + \frac{mP_m\tau_{\rm es}}{V\sqrt{C_{\rm ph}^2 + (2\pi f_m)^2\tau_{\rm es}^2 C^2}}\sin(2\pi f_m t + \phi) \\ & + \frac{2\pi m P_m \tau_{\rm es}^2 C f_m}{V(C_{\rm ph}^2 + (2\pi f_m)^2\tau_{\rm es}^2 C^2)}\exp\left(-\frac{C_{\rm ph}}{C\tau_{\rm es}}\,t\right)\end{aligned} \tag{8}$$

where

$$\phi = -\tan^{-1}\left(\frac{2\pi C\tau_{\mathrm{es}} f_m}{C_{\mathrm{ph}}}\right).$$

It is seen that in the steady-state regime, the temperature of the HTS film can be modulated by the optical radiation, so called thermomodulation effect. This fact was theoretically discussed by Perrin [22], experienced by Venneste *et al.* for conventional superconductors [23] and Danerud *et al.* for YBaCuO epitaxial film [24].

C. Pulsed Optical Irradiation

During the last decade, particular attention has been devoted to the HTS photoresponse subject to the picosecond and nanosecond laser pulses. Most of the experiments have shown nonbolometric response and the bolometric tail due to the time constant of the applied optical pulse comparable with the electron–phonon relaxation time [25]. Here, we assume that a laser source provides an optical pulse with the Gaussian temporal profile with a time constant τ. In order to take an advantage of the fast bolometric response, the time constant of the pulse must be greater than the electron–phonon relaxation time [7]. Upon this condition, the absorbed optical power can be considered as:

$$P_a(t) = P_m \exp\left(-\frac{(t-t_d)^2}{2\tau^2}\right) \tag{9}$$

where t_d is a time delay of a pulse.

Solution of (1), gives us the temperature shift as follows:

$$\begin{aligned}\Delta T(t) = &\frac{\sqrt{2\pi}P_m\tau}{2CV}\,\mathrm{erf}\left(\frac{\sqrt{2}t}{2\tau}-\alpha\right)\\ &\cdot\exp\left(-\frac{C_{\mathrm{ph}}}{C\tau_{\mathrm{es}}}t-\frac{t_d^2}{2\tau^2}+\alpha^2\right)\\ &+\frac{\sqrt{2\pi}P_m\tau}{2CV}\,\mathrm{erf}(\alpha)\exp\left(-\frac{C_{\mathrm{ph}}}{C\tau_{\mathrm{es}}}t+\beta\right)\end{aligned} \tag{10}$$

where $\mathrm{erf}(.)$ is the error function

$$\alpha = \frac{\sqrt{2}}{2}\left(\frac{t_d}{\tau}+\frac{C_{\mathrm{ph}}\tau}{C\tau_{\mathrm{es}}}\right) \text{ and } \beta = \frac{C_{\mathrm{ph}}}{2C}\left(\frac{2t_d}{\tau_{\mathrm{es}}}+\frac{C_{\mathrm{ph}}\tau^2}{C\tau_{\mathrm{es}}^2}\right).$$

As will be seen later on, our analytic solution is in a complete agreement with the experiments [13], [26] and a quantitative analysis presented in [7], [9].

Generally, a pulsed laser source consists of a train of the Gaussian pulse by the interpulse time interval T or a repetition rate $f = 1/T$. If P_{av} is the average optical power in the pulse train, then the instantaneous absorbed optical power in the HTS film by the contribution at a time, t, due to all of the pulses in the infinite train is given by [27]

$$P_a(t) = \frac{P_{\mathrm{av}}}{\sqrt{2\pi}}\,\frac{T}{\tau}\sum_{n=-\infty}^{+\infty}\exp\left(-\frac{(t-t_d+nT)^2}{2\tau^2}\right). \tag{11}$$

If this is the case, when the interpulse interval time T is greater than the bolometric response time τ_{th}, the temperature shift can be simply written by means of the superposition of the temperature shift presented in formula (10) shifted at time nT, and the average power P_{av} is accountable for the average temperature shift in the HTS film.

As most of the mode locked or Q-switched high power lasers are employed at the MHz repetition rate, for the nanosecond photoresponse time the discussed analysis would be applicable.

IV. Optical-Microwave Interaction in HTS Films

The microwave properties of superconductors are well-understood theoretically and experimentally. The electrodynamic theory of superconductors was originally established by London [28]. This macroscopic theory essentially incorporates the zero resistance and perfect diamagnetism of superconductors into electromagnetic constitutive relations. The basic idea of this phenomenological theory is the two-fluid model presented by Gorter and Casimir in 1934. According to the two-fluid model, the electron fluid is composed of Cooper pairs at the lowest energy state and normal electrons in the excited state. The number of carriers is dependent on the temperature and can be given by the following empirical relations [29]:

$$n_s(T) = n\left(1-\left(\frac{T}{T_c}\right)^{\gamma}\right) \tag{12}$$

$$n_n(T) = n\left(\frac{T}{T_c}\right)^{\gamma} \tag{13}$$

where n_s and n_n are the Cooper pair and normal electron number densities, n is the total electron number density, and γ is an exponent. For conventional superconductors such as Pb and Nb, $\gamma \approx 4$ and for most HTS materials such as YBaCuO, $\gamma \approx 2$ has been suggested. Under the application of an external electric field, the movement of the Cooper pairs are purely inertial but the motion of the normal electrons includes the effects of both inertial and resistance due to their collision with the lattice. When the applied electric field $\mathbf{E}$ has a period of oscillation much smaller than the electron–phonon relaxation time, τ_{e-ph}, the carrier velocities $\mathbf{v_s}$, and $\langle\mathbf{v_n}\rangle$ can be given by [29]

$$\mathbf{v_s} = -\frac{e}{m}\int \mathbf{E}\,dt \tag{14}$$

and

$$\langle\mathbf{v_n}\rangle = -\frac{e\tau_{e-ph}}{m}\,\mathbf{E} \tag{15}$$

where e and m are the charge and the mass of an electron, respectively. The total current density produced by the external electric field consists of two noninteracting currents namely superfluid and normal currents as:

$$\mathbf{J} = \mathbf{J_s}+\mathbf{J_n} = -e(n_s\mathbf{v_s}+n_n\langle\mathbf{v_n}\rangle). \tag{16}$$

The equivalent circuit model for the superconducting medium is then consisted of the kinetic inductance L_k indicating the presence of the Cooper pairs and the resistance R_n presenting the effect of normal electrons, as illustrated in Fig. 3 [30]. When the superfluid is much greater than the normal current, the normal electrons are moving within the diffusion skin depth and experiencing the lattice collision due to the skin effect, while the Cooper pairs are flowing within the London penetration depth without any collision, due to the screening effect [31]. In this case, the impedance of the kinetic inductance is much greater than the resistance and the London penetration depth is very smaller than the diffusion skin depth. According to the two-fluid model the London penetration depth is frequency independent and can be written as [30]

$$\lambda_L^2(T) = \frac{L_k}{\mu_o} = \frac{m_s}{e_s^2 \mu_o n_s(T)} \tag{17}$$

where m_s and e_s are the mass and the charge of Cooper pair, respectively, and L_k is the kinetic inductance in $\mathrm{H} \cdot \mathrm{m}$. Since the London penetration depth is much smaller than the diffusion skin depth, this implies that the conduction process and consequently the current flow is mainly focused within the London penetration depth. This physical picture is very useful when the applied electromagnetic field does not cause any nonlinearity in the superconducting medium and its frequency is well below the gap frequency.

Back to the photoexcited HTS film and comparing the optical penetration depth with the London penetration depth, one can deduce that the current flow in the HTS film is seriously affected by the optical irradiation. Therefore, since the HTS film acts as a transmission line for any applied microwave signal, the optical irradiation perturbs the conduction process by Cooper pair breaking or macroscopically raising the temperature and leads to manipulation of the microwave signal. By the extension of the kinetic inductance bolometric model [13], an absorbed optical irradiation will break the Cooper pairs, reduce the population of the Cooper pair number density n_s and increase the normal electron number density n_n , via the temperature shift analyzed in the previous section and (12) and (13), while their velocity is determined by the microwave electric field $\mathbf{E}$. The current can then be written as

$$\mathbf{J} = \frac{e^2}{m}\left(n_s(t)\int \mathbf{E}\,dt + n_n(t)\tau_{e-ph}\mathbf{E}\right). \tag{18}$$

Since the characteristics of the optical radiation source and the input microwave signal are given, (18) gives the current-field relationship in the HTS film, due to the presence of both optical and microwave signals. The time required for photoexcited normal electrons to contribute to the normal current identifies the speed of interaction between optical radiation and microwave signal. It is worth mentioning that the supercurrent response time τ_J can be estimated by the equivalent circuit model presented in Fig. 3 [32]. When the number of Cooper pairs is decreased, the kinetic inductance will be increased and the normal-fluid channel resistance will shunt current away from the L_k. Thus, the supercurrent will respond to the optical irradiation in a time

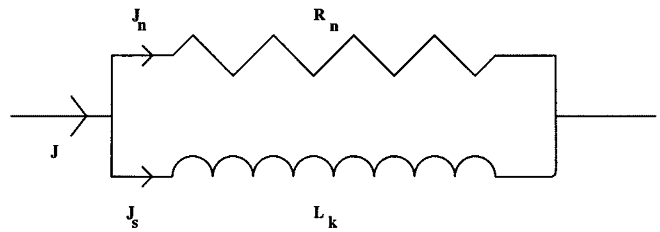


Fig. 3. Circuit representation of the two-fluid model for superconductors.

$$\tau_J = \frac{L_k}{R_n} = \tau_{e-ph}\frac{\left(\dfrac{T}{T_c}\right)^{\gamma}}{1-\left(\dfrac{T}{T_c}\right)^{\gamma}}. \tag{19}$$

Note that the discussed model assumes the lumped model for both thermal and electrical parts and does not consider the traveling-wave type of optical-microwave interaction in the HTS films. In order to observe the capability of the developed model, our discussion will be proceeded by the numerical simulation of this type of interaction in the HTS microstrip structure and the results will be compared with the experimental works existed in the literature.

V. Numerical Simulations

Consider a thin superconducting film made of oxygen-rich YBaCuO deposited on a substrate, normally $LaAlO_3$ or MgO. The thickness of the film is much smaller than the substrate thickness, and the YBaCuO film is employed in a microstrip and microbridge configuration as depicted in Fig. 4. This type of structure has been used in many experiments related to the photoresponse measurements [13], [33]. All of the geometrical and physical parameters are listed in Table I. The geometrical parameters of YBaCuO microstrip are taken from [13]. We consider the geometrical parameters presented in Table I, in order to minimize the effect of magnetic inductance and nonuniformity of the current distribution along the microstrip line by choosing $w \gg h$ [19]. Although the current distribution for HTS microstrip structure is nonuniform especially near its edges [34], but the peak current density is only about twice the average value, since the minimum current density takes place at the center and is about 0.75 the average value for a thin microstrip [35]. It has been recently shown that if the temperature is changed or the optical radiation is absorbed, the shape of the current distribution through the thickness of the film changes everywhere uniformly except within λ_L of the edges [36]. Therefore the assumption of uniform current density is not an unreasonable approximation. The length of the bridge is also chosen smaller than the microwave wavelength to guarantee the validity of the electrically lumped model and greater than out-diffusion length, $\sqrt{12D\tau_{e-ph}}$. The main goal in achieving such a conditions is to alleviate the transmission line effects on the propagation of microwave signals along the structure. This helps to verify and observe the physical phenomenon that takes place in the optical-microwave interaction in the HTS films.

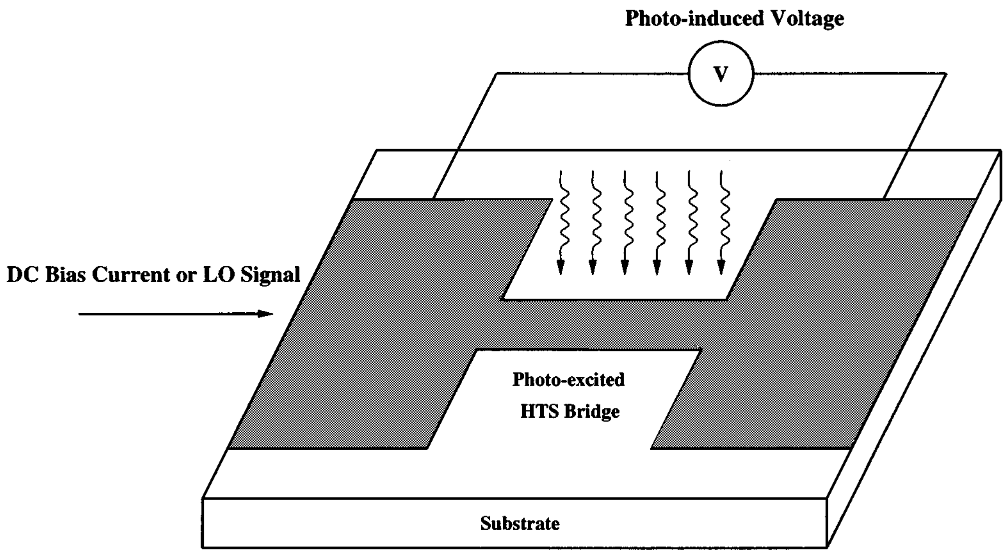


Fig. 4. Photoexcited HTS film and its electrical configuration.

TABLE I
PARAMETERS USED IN THE ANALYSIS OF PHOTO EXCITED YBaCuO FILM

Description	Value
Initial Temperature (T_o)	73 K
Critical Temperature (T_c)	86 K
Exponent (γ)	2
Critical Current (I_c)	5 mA
Bridge Width (w)	10 μm
Bridge Length (l)	20 μm
Film Thickness (d)	30 nm
Dielectric Spacer (h)	1 μm
London Penetration Depth (λ_0)	$\approx$ 180 nm
Optical Wavelength	532 nm
Optical Penetration Depth (δ_o)	90 nm
Optical Reflection Coefficient(R)	$\approx$ 0.2
Heat Capacity (C)	0.91 $\mathrm{Jcm^{-3}K^{-1}}$
Phonon Heat Capacity (C_{ph})	0.9 $\mathrm{Jcm^{-3}K^{-1}}$
Phonon Escape Time (τ_{es})	1 ns

The output of a laser source is focused on the bridge such that it is illuminated uniformly. The microwave signal is applied to the bridge from the current source, and the voltage across the bridge should be monitored by a fast, sensitive and high frequency oscilloscope. According to the current-field relation (18), if the electrical current through the bridge part is assumed to be $i(t)$ much smaller than the critical current, then by ignoring the normal current, the voltage $v(t)$ across the bridge will be

$$v(t) = L(t)\,\frac{di(t)}{dt} + i(t)\,\frac{d}{dt}\,L(t) \tag{20}$$

where $L(t)$ denotes the time dependent inductance due to the optical irradiation and for a microstrip line can be expressed as [37]

$$L(t) = L_m + L_k(t) = \frac{\mu_0 hl}{2w}\left(1 + 2\,\frac{\lambda_L(t)}{h}\coth\left(\frac{d}{\lambda_L(t)}\right)\right) \tag{21}$$

where L_m and L_k are the magnetic and kinetic inductances of the HTS strip. It is seen that the optical stimulation affects the kinetic inductance part via the time dependent London penetration depth. The time dependent London penetration depth is then calculated through the temperature $T(t)$ obtaining from the Sections III-A–C for different types of the optical source.

At the first step, we consider a periodic optical irradiation in the presence of either dc bias current I_o and a pure sinusoidal microwave current with 1-mA amplitude. The absorbed optical power with modulation frequency $f_m = 100$ MHz, unity modulation index and peak power 35 mW is considered, and the steady state photoinduced temperature in the HTS bridge is calculated by (8). Under the application of such an optical signal, the temperature is modulated periodically and controlled by the optical power when the HTS bridge still remains in the superconducting state. Fig. 5 illustrates the voltage response, when the HTS bridge is biased with 1mA dc current and a microwave local oscillator (LO) with frequency $f_{\mathrm{LO}} = 300$ MHz, respectively. Further investigation of the photoinduced voltage in the frequency domain reveals that, because of the nonlinear relationship between the kinetic inductance and the temperature, the photoinduced voltage has harmonic frequencies of the modulation frequency of the optical signal, as depicted in Fig. 6 when the bridge is biased by dc current. Our simulation indicates that there is a strong second harmonic component of the modulation frequency, due to the second order nonlinearity of the penetration depth with temperature and time derivative relationship between the kinetic inductance and voltage, which amplifies the harmonic frequency in the output voltage. This promises the feasibility of microwave harmonic generation in the HTS film

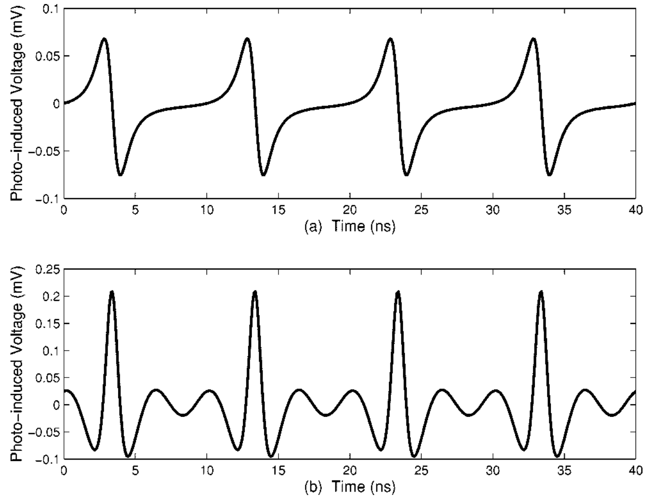


Fig. 5. Photoinducted steady-state voltage response of HTS bridge. (a) With 1-mA dc-bias current. (b) 300-MHz LO current.

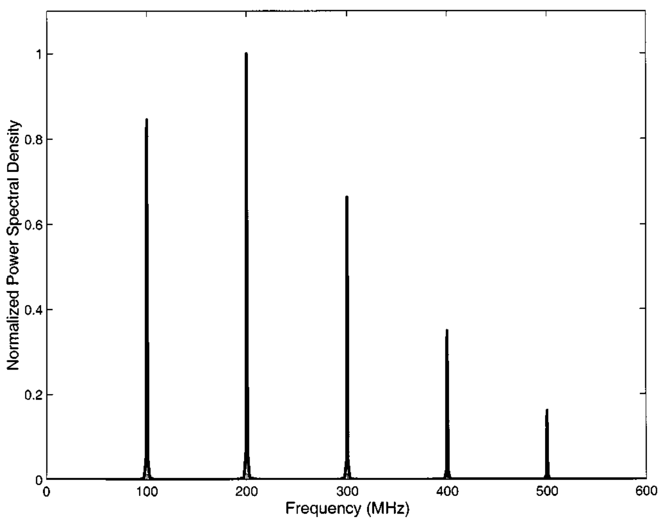


Fig. 6. Normalized spectral density of photoinducted voltage in the presence of 1-mA dc-bias current.

by the optoelectronic technique. If the LO current is fed to the HTS bridge, the photoinduced voltage is the mixed version of the modulation frequency f_m and LO frequency. Fig. 7 indicates the frequency spectrum of the output voltage in the absence of the main components. It is worth noting that because normally the first term in relation (20) is greater than its second term, the amplitude of the voltage in sum and difference frequencies ($f_{\rm LO} \pm f_m$) are not the same. Since the temperature of the HTS film will approach its critical value by the absorbed optical power, the amplitudes of the harmonic frequencies become highly dependent on the absorbed optical power and initial temperature. When the HTS film is driven near its transition point to the normal state, frequency harmonics will become stronger. If the photoexcited HTS bridge is illuminated by the critical absorbed optical power or higher, the photoresponse is no longer kinetic inductive and the developed voltage is due to the change in the resistivity of the HTS film. This simulation demonstrate potentials of an optoelectronic HTS mixer in up and down conversion of RF signals in high performance superconducting microwave/photonic systems.

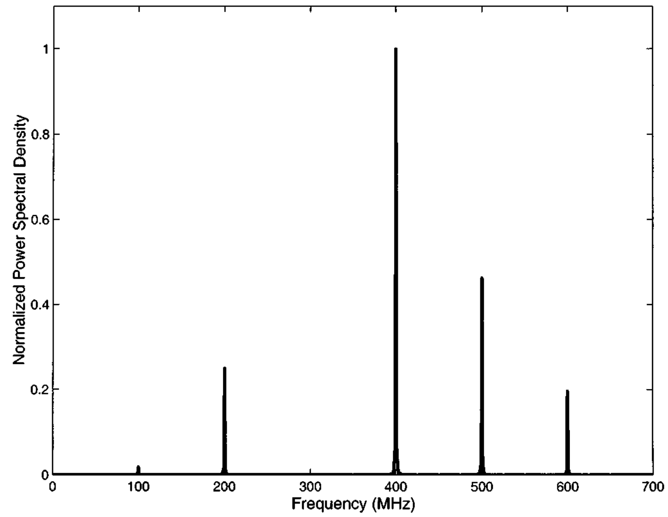


Fig. 7. Normalized spectral density of photoinducted voltage in the presence of 1-mA LO current.

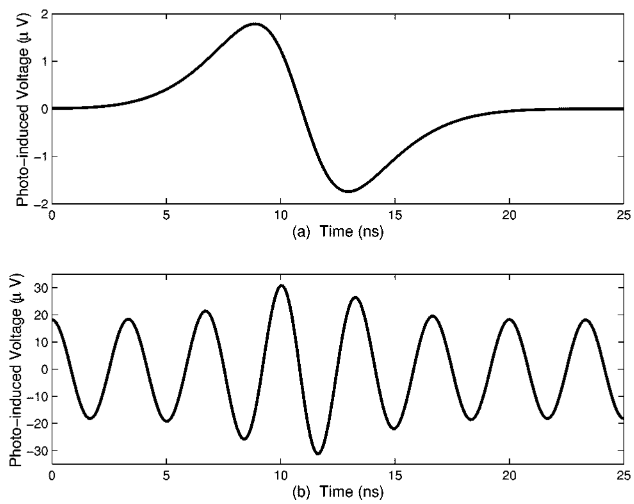


Fig. 8. Voltage response of HTS bridge to the pulsed optical irradiation. (a) With 1-mA dc-bias current. (b) 300-MHz LO current.

In the second step, the optical pulsed radiation with the absorbed peak power 100 mW and time constant $2\sqrt{2}$ ns is incident on the HTS bridge. Fig. 8 indicates the photoinduced voltage, when the HTS bridge is biased with 1 mA dc current and LO signal with frequency $f_{\rm LO} = 300$ MHz, respectively. The fast bipolar transient voltage developed across the bridge, inherently acts as an HTS photodetector and optical-to-electrical transducer for employing in digital communications using rapid single-flux-quantum (RSFQ) circuits and optical fiber for high-speed data transmission into the cryogenic environment [26].

If the HTS film is mounted on a substrate with low dielectric constant such as MgO, the transient alteration in the temperature of the HTS film produces an RF pulsed radiation. The radiation field is proportional to the time derivative of the current for our considered structure presented in Fig. 4. The duration of the emitted electromagnetic pulse depends on the supercurrent response time, τ_J, and could be enhanced up to the picosecond time scale or terahertz radiation from optically excited YBaCuO film [15], [38]. When the LO signal is connected to the HTS photoexcited bridge the amplitude of the voltage is modulated by the optical pulse leading to optoelectronic amplitude modulation. This technique can also be used for microwave signal processing and tunability of the HTS microwave devices such as delay lines and resonators, since the temperature and subsequently the electrical parameters of such a devices can be controlled via the optical irradiation [39], [40].

VI. Conclusion

We have developed a theoretical framework for investigating the optical-microwave interaction in HTS films. Generally, the optical signal with frequency greater than the gap frequency of the HTS material affects the conduction process by breaking the Cooper pairs. While the superconductivity is controlled by the optical radiation, the microwave signal traveling in the HTS film is being manipulated through the variation of superconducting and normal carriers by photoabsorption phenomenon. The interaction of light with HTS film was theoretically studied by the thermal analysis, since the absorption of optical radiation can be macroscopically considered by the temperature raise. The HTS photoresponse from three different optical sources was investigated. It has been demonstrated that in all cases the temperature shift replicates the variation of the optical power waveform, so called the thermomodulation effect. Then, the propagation of the microwave signal in the photoexcited HTS film was considered through the two-fluid model. In this framework, the number of Cooper pairs and normal electrons are controlled by the optical radiation and their velocity are assigned by the microwave signal. Therefore, the super and normal currents are highly dependent on the variation of both optical and electrical signals. The combined lumped heat transfer and electrical model has been developed in the HTS microstrip and bridge configuration. Our numerical simulations in such a structure, demonstrate the feasibility of performing optoelectronic functions in HTS films such as photodetection, RF harmonic generation and mixing, optical-to-electrical transducing and RF burst generation as well as optical control of HTS microwave devices.

References

[1] R. Sobolewski, "Prospects for high-T_c superconducting optoelectronics," in *Superconductivity and Its Applications, AIP Conf. Proc. 251*, Y. H. Kao, A. E. Kaloyeros, and H. S. Kwok, Eds. College Park, MD: Amer. Inst. Phys., 1992, pp. 659–670.

[2] C. H. Lee, "Picosecond optics and microwave technology," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 596–607, May 1990.

[3] P. H. Ballentine, A. M. Kadin, and W. R. Donaldson, "Sputtered high-T_c superconducting films as fast optically triggered switch," in *Superconductivity and Applications*, H. S. Kwok, Y. H. Kao, and D. T. Shaw, Eds, New York: Plenum, 1990, pp. 685–693.

[4] Y. S. Lai *et al.*, "500 Hz picosecond inductive energy storage pulsed power system using a high T_c superconductor opening switch," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 1255–1257, Oct. 1994.

[5] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, "Theory of superconductivity," *Phys. Rev.*, vol. 108, no. 5, pp. 1175–1204, 1957.

[6] A. V. Sergeev and M. Y. Reizer, "Photoresponse mechanisms of thin superconducting films and superconducting detectors," *Int. J. Mod. Phys. B*, vol. 10, no. 6, pp. 635–667, 1996.

[7] A. Frenkel, "Mechanisms of nonequilibrium optical response of high temperature superconductors," *Phys. Rev. B, Condens. Matter*, vol. 48, no. 13, pp. 9717–9725, 1993.

[8] D. E. Prober, "Superconducting terahertz mixer using a transition-edge microbolometer," *Appl. Phys. Lett.*, vol. 62, no. 17, pp. 2119–2121, 1993.

[9] A. D. Semenov *et al.*, "Analysis of the nonequilibrium photoresponse of superconducting films to pulsed radiation by use of a two-temperature model," *Phys. Rev. B, Condens. Matter*, vol. 52, no. 1, pp. 581–590, 1995.

[10] C. J. Stevens *et al.*, "Evidence of two-component high-temperature superconductivity in the femtosecond optical response of $YBa_2Cu_3O_{7-\delta}$," *Phys. Rev. Lett.*, vol. 78, no. 11, pp. 2212–2215, 1997.

[11] E. M. Gershenzon *et al.*, "Light-induced heating of electrons and the time of the inelastic electron–phonon scattering in the YBaCuO compound," *JETP Lett.*, vol. 46, pp. 285–287, 1988.

[12] N. Bluzer, "Temporal relaxation measurements of Photoinduced nonequilibrium in superconductors," *J. Appl. Phys.*, vol. 71, no. 3, pp. 1336–1348, 1992.

[13] F. A. Hegmann and J. S. Preston, "Origin of the fast photoresponse of epitaxial $YBa_2Cu_3O_{7-\delta}$ thin films," *Appl. Phys. Lett.*, vol. 48, no. 21, pp. 16 023–16 039, 1993.

[14] M. J. Holcomb, J. P. Collman, and W. A. Little, "Optical evidence of an electronic contribution to the pairing interaction in superconducting $Tl_2Ba_2Ca_2Cu_3O_{10}$," *Phys. Rev. Lett.*, vol. 73, no. 17, pp. 2360–2363, 1994.

[15] M. Hangyo *et al.*, "Ultrafast optical response and terahertz radiation from high-T_c superconductor," *IEICE Trans. Electron*, vol. E80-C, no. 10, pp. 1282–1290, 1997.

[16] H. Yasuoka *et al.*, "Optical absorption spectra of single-crystal YBaCuO films," *Phys. C*, vol. 175, no. 1 & 2, pp. 192–196, 1991.

[17] G. L. Carr *et al.*, "Fast bolometric response by high-T_c detectors measured with subnanosecond synchrotron radiation," *Appl. Phys. Lett.*, vol. 57, no. 25, pp. 2725–2727, Aug. 1990.

[18] J. Kawamura *et al.*, "Low noise NbN lattice-cooled superconducting hot electron bolometric mixers at submillimeter wavelengths," *Appl. Phys. Lett.*, vol. 70, no. 12, pp. 1619–1621, 1997.

[19] F. A. Hegmann, "Picosecond photoresponse of high-T_c superconducting thin films," Ph.D. dissertation, McMaster Univ., Hamilton, ON, Canada, 1994.

[20] R. C. Chen *et al.*, "Bolometric response of high-T_c superconducting detectors to optical pulses and continuous waves," *J. Heat Transfer*, vol. 117, pp. 366–372, 1995.

[21] Y. Liu *et al.*, "Pulsed terahertz-beam spectroscopy as a probe of the thermal and quantum response of YBaCuO superfluid," *Appl. Phys. Lett.*, vol. 67, no. 20, pp. 3022–3024, 1995.

[22] N. Perrin and C. Vanneste, "Response of superconducting films to a periodic optical irradiation," *Phys. Rev. B, Condens. Matter*, vol. 28, no. 9, pp. 5150–5159, 1983.

[23] C. Venneste *et al.*, "Dynamic behavior of optically induced superconducting weak links," *Appl. Phys. Lett.*, vol. 38, no. 11, pp. 941–942, 1981.

[24] M. Danerud *et al.*, "Nonequilibrium and bolometric photoresponse in patterned $YBaCuO_{7-\delta}$ thin films," *J. Appl. Phys.*, vol. 76, pp. 1902–1909, 1994.

[25] F. A. Hegmann and J. S. Preston, "Identification of nonbolometric photoresponse in $YBa_2Cu_3O_{7-\delta}$ thin films based on magnetic field dependence," *Appl. Phys. Lett.*, vol. 62, no. 10, pp. 1158–1160, 1993.

[26] M. Lindgren *et al.*, "Ultrafast photoresponse in microbridges and pulse propagation in transmission lines made from high-T_c superconducting thin films," *IEEE J. Select. Topics Quantum Electron.*, vol. 2, pp. 668–678, Sept. 1996.

[27] W. M. Robertson, *Optoelectronic Techniques for Microwave and Millimeter-Wave Engineering*, MA: Artech-House, 1995, p. 227.

[28] F. London, *Superfluids*, New York: Dover, 1961.

[29] O. G. Vendik, I. B. Vendik, and D. I. Kaparkov, "Empirical model of microwave properties of high temperature superconductors," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 469–478, May 1998.

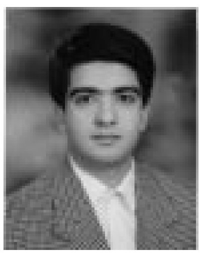
[30] T. Van Duzer and C. W. Turner, *Principles of Superconductive Devices and Circuits*, 2nd ed. Amsterdam, The Netherlands: Elsevier, 1999, sec. 3.14.

[31] T. P. Orlando and K. A. Delin, *Foundations of Applied Superconductivity*. Reading, MA: Addison-Wesley, 1991, sec. 3.4.

[32] A. M. Kadin and A. M. Goldman, "Dynamical effect in nonequilibrium superconductors: Some experimental perspectives," in *Nonequilibrium Superconductivity*, D. N. Langenberg and A. I. Larkin, Eds. Amsterdam, The Netherlands: Elsevier, 1986, pp. 253–324.

[33] W. R. Donaldson *et al.*, "Interaction of picosecond optical pulses with high T_c superconducting films," *Appl. Phys. Lett.*, vol. 54, no. 24, pp. 2470–2472, 1989.

[34] S. Safavi-Naeini, R. Faraji-Dana, and Y. L. Chow, "Studies of edge current densities in regular and microstrip lines of finite thickness," *Proc. Inst. Elect. Eng.*, vol. 140, no. 5, pp. 361–366, 1993.
[35] T. R. Lemberger, "Films of high-temperature oxide superconductors," in *Physical Properties of High Temperature Superconductors III*, D. M. Ginzburg, Ed, Singapore: World Scientific, 1992, pp. 471–523.
[36] J. C. Culberston, H. S. Newman, and C. Wilker, "Optical probe of microwave current distribution in high temperature superconducting transmission lines," *J. Appl. Phys.*, vol. 48, no. 5, pp. 2768–2787, 1998.
[37] J. M. Pond, J. H. Claasen, and W. L. Carter, "Measurements and modeling of kinetic inductance microstrip delay lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 1256–1262, 1987.
[38] C. Jaekel, G. Roskos, and H. Kurz, "Emission of picosecond electromagnetic pulses from optically excited superconductive bridges," *Phys. Rev. B, Condens. Matter*, vol. 54, no. 10, pp. 6889–6892, 1996.
[39] S. Cho and H. R. Fetterman, "Optically tuned propagation delay in YBaCuO superconducting delay lines," *IEEE Trans. Appl. Superconduct.*, vol. 7, pp. 2454–2457, June 1997.
[40] T. Sindlekht *et al.*, "Frequency modulation of the superconducting parallel-plate microwave resonator by laser irradiation," *Appl. Phys. Lett.*, vol. 65, no. 22, pp. 2875–2877, 1994.



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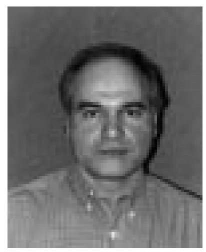

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