Optoelectronic RF Harmonic Generation and Mixing in High-T_c Superconducting Film

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ABSTRACT

We demonstrate for the first time the possibility of RF harmonic generation and signal mixing in HTS thin films by optoelectronic technique. Using HTS photoresponse, the inductance of the HTS film is modulated by an RF carrier frequency, which is the envelope of the optical signal. In the presence of a DC or sinusoidal current, second harmonic generation and RF signal mixing are achieved respectively using YBaCuO thin film by temporal and frequency analysis. This novel device can be useful for low-noise/low-power HTS microwave-photonic systems and interconnects.

I. INTRODUCTION

With the advent of photonic technology and realization of HTS microwave devices, there is a possibility for integration of these two disciplines to perform high-speed/high frequency and low-noise/low-power electronic functions in cryogenic environment. The fast bolometric photoresponse in the HTS materials provides a nonlinear interaction to permit the coupling between the optical and electrical signals. In this case, incident optical radiation raises the temperature of the HTS film by breaking the Cooper pairs and results in a change in the electrical properties [1]. Since the optical signal is modulated by an RF carrier signal, the electrical parameters of the HTS film, most importantly the kinetic inductance, is subsequently modulated, leading to create harmonic generation and mixing phenomena in the presence of RF local oscillator signal passing through the HTS film. In this manuscript, we propose the RF-optoelectronic HTS device configuration , modeling and simulation. The optical signal is modulated by a carrier frequency f_c and the HTS film is either biased with the DC current to produce harmonics of the carrier frequency or pure unmodulated sinusoidal current at frequency f_{LO} to produce mixed signal. We will develop our proposal with the simulation of such a device based on YBaCuO thin film and compare our results with the existing experimental results available in the literature.

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II. Device Configuration and Modeling

Consider an HTS film deposited on a dielectric substrate, as depicted in Fig 1. A current source supplies a bias current $i(t)$ to the bridge part and sensitive voltmeter or oscilloscope measures the voltage $v(t)$ across the bridge. This structure is intended to operate at temperature range $0.5T_c < T < 0.9T_c$ and far below its critical values of current and magnetic field. A laser beam modulated by an RF signal illuminates the bridge part uniformly. As the optical power flows through the HTS film, a fraction of the absorbed optical power within the optical penetration depth δ_o acts as an internal heat source, creating heat diffusion in the HTS film/substrate. The photo-induced excess heat is then dissipated through the substrate. According to the energy conservation law, the temperature shift $\Delta T(t)$, can be written as follows [2]:

$$C\frac{d}{dt}\Delta T(t) = \alpha\frac{P_o(t)}{V} - \frac{C_{ph}}{\tau_{es}}\Delta T(t) \qquad (1)$$

where C is the heat capacity of the HTS film, α is optical absorptivity, $P_o(t)$ is the optical power, V is the volume of photo-excited portion of the bridge, C_{ph} is the phonon heat capacity and τ_{es} is the phonon escape time. The phonon escape time indicates the time required for transferring the excess heat out of the photo-excited region through the substrate and is related to the thermal boundary resistance, R_{BD} by [3]:

$$\tau_{es} = CdR_{BD} \qquad (2)$$

where d is the film thickness. Depending on the film thickness, geometry and the substrate, τ_{es} might vary from milliseconds to picoseconds [2]. When the initial temperature is T_0, then the time dependent temperature of the HTS film can be expressed as, $T(t) = T_0 + \Delta T(t)$. If the optical signal is sinusoidally modulated at carrier frequency f_c as $P_o(t) = P_o(1 + \sin 2\pi f_c t)$, then by solving equation (1), the steady state temperature of the bridge can be written as:

$$\begin{aligned} T(t) &= T_0 + \frac{\alpha P_o \tau_{es}}{C_p V} \\ &+ \frac{\alpha P_o \tau_{es}}{V\sqrt{C_p^2 + \omega_m^2\tau_{es}^2 C^2}}\sin(2\pi f_c t + \phi) \end{aligned} \qquad (3)$$

where $\phi = -\tan^{-1}(\frac{C\tau_{es}\omega_m}{C_p})$.

The above analysis is in complete agreement with the previous works done by N. Perrin and C. Vanneste for conventional superconductors [4]. As the temperature of the HTS film is temporally altered, the number of Cooper pairs and subsequently the penetration depth, $\lambda_L(T)$, is changed with time as [5]:

$$\lambda_L(t) = \frac{\lambda_0}{\sqrt{1 - (\frac{T(t)}{T_c})^\gamma}} \qquad (4)$$

where λ_0 is penetration depth at zero temperature and γ is an empirical exponent. If the dielectric thickness (h) and penetration depth are small compared to the width (w) of the HTS strip, the inductance (L) of the strip is [6]:

$$L(t) = \frac{\mu_0 hl}{2w}\Big(1 + 2\frac{\lambda_L(t)}{h}\coth(\frac{d}{\lambda_L(t)})\Big) \qquad (5)$$

where l is the length of the bridge part. Equation (5) implies that the kinetic inductance part of the bridge is modulated by the optical irradiation via the temperature modulation. This fact was experimentally confirmed by Hegmann and Preston and referred to as kinetic inductance photoresponse [3]. Ignoring the normal current, the voltage across the HTS bridge would be:

$$v(t) = L(t)\frac{d}{dt}i(t) + i(t)\frac{d}{dt}L(t) \qquad (6)$$

where $i(t)$ is the current of the bridge. Since the photo-induced voltage appears due to the nonlinear inductive photoresponse, it contains the harmonics of the carrier frequency f_c for DC bias current, and mixed version of carrier and LO frequencies when the HTS bridge is connected to the LO current source. The exponent γ in relation (4) determines which harmonics and mixed frequencies appear in the spectral domain of the photo-induced output voltage.

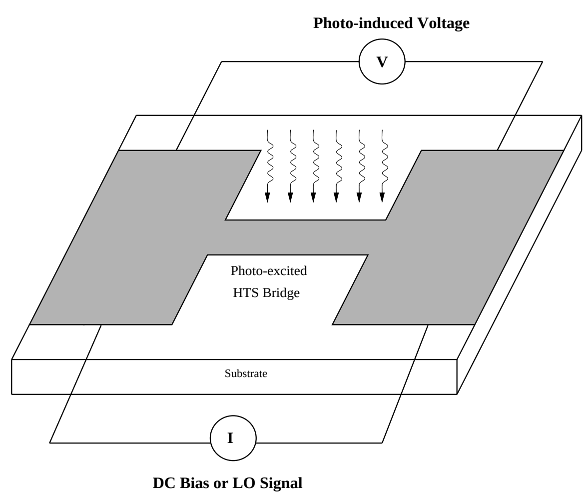

Figure 1: Photo-excited HTS film and its electrical configuration

III. Simulation Results

We consider YBaCuO thin films deposited on the LaAlO substrate with the geometrical dimensions and thermodynamical parameters presented in [3]. All of the required parameters are listed in Table 1. It is assumed that the optical wavelength 532 nm is modulated by a pure sinusoidal waveform with frequency $f_c = 100$ MHz. In the first step, the HTS film is biased with 1 mA DC current and the photo-induced voltage is observed. Temporal and frequency analysis reveal that the photo-induced voltage is a bipolar periodic waveform which contains second and third harmonics. The power spectral density of voltage is plotted in Fig 2. It is seen that 5% of the output power is sitting at 200 MHz. This configuration can be effectively employed for RF second harmonic generation. In the second step, a pure sinusoidal current with amplitude 1 mA and frequency $f_{LO} = 300$ MHz is applied to the bridge. In this case, the output voltage clearly indicates the mixed frequency, which is illustrated in Fig 3. Because of the second order nonlinearity between temperature and the inductance of the HTS bridge the frequencies $f_{LO} \pm f_c$ and $f_{LO} \pm 2f_c$ appeared in the frequency domain. These results demonstrate potentials of an optoelectronic HTS mixer in up and down convertion of RF signals for optical subcarrier multiplexed systems [7].

Description	Value
Initial Temperature (T_0)	73 K
Critical Temperature (T_c)	90 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)	180 nm
Optical Penetration Depth (δ_o)	90 nm
Optical Absorptivity (α)	0.8
Optical Power (P_o)	37.5 mW
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

Table 1: Parameters used in the analysis of Photo-excited YBaCuO film.

IV. Device Characteristics

Performance of the optoelectronic HTS mixer can be verified and compared by other mixers based on the

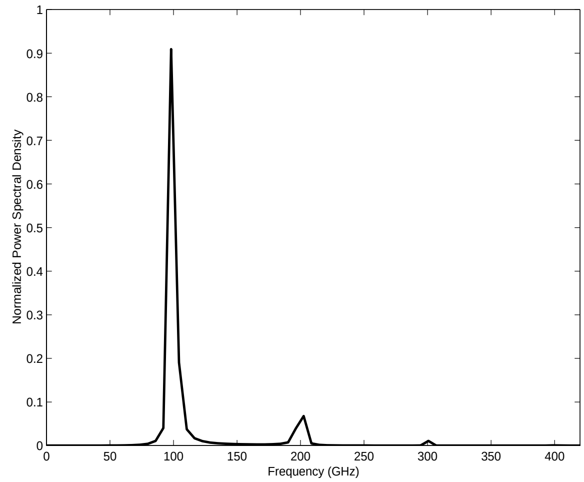

Figure 2: Power Spectral density of photo-induced output voltage

conversion gain bandwidth, intrinsic and extrinsic conversion gains and equivalent noise temperature. The conversion gain bandwidth of our proposed device can be found from the bolometric transient response as:

$$B_G = \frac{1}{2\pi}\frac{C_{ph}}{C\tau_{es}} \qquad (7)$$

Effective reduction of phonon escape time results in higher bandwidth even up to THz frequencies similar to the superconducting hot-electron bolometric mixers (HEB) [8]. Nearly perfect isolation between the LO signal and RF carrier signal causes the lack of coupling loss, which increases the intrinsic conversion gain in comparison with HEB mixers, but is less than optoelectronic mixer based on semiconducting heterojunction bipolar transistors (HBT). The extrinsic conversion gain is even higher than HBT, because of higher amount of light absorption in YBaCuO thin films and higher quantum efficiency [9]. The equivalent output noise temperature (T_{FL}) dissipated in a perfectly matched load R_L caused by the temperature fluctuations in the HTS optoelectronic mixer is given by:

$$T_{FL} = \frac{4\pi^2 f_{LO}^2 i_m^2}{R_L}\frac{T^2\tau_{es}}{CV}\left(\frac{dL}{dT}\right)^2 \qquad (8)$$

where i_m is the maximum LO current. As it is expected T_{FL} is comparable with HEB mixers and approaches to the ten times of the quantum noise limit,

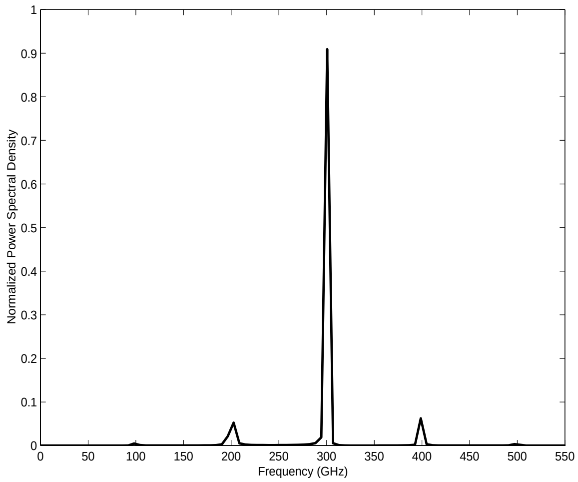

Figure 3: Power Spectral density of photo-induced output voltage

depending on the initial temperature, RF carrier frequency and phonon escape time [10].

V. CONCLUSION

We have proposed a novel optoelectronic RF harmonic generation and mixer based on HTS thin film. It is shown that in the presence of a DC bias current, the photo-induced voltage signal contains harmonics of the carrier frequency. When the HTS bridge is driven by a sinusoidal wave with LO frequency, the output voltage contains the mixed frequency including the up and down converted frequencies. The theoretical performance of such a device with the experimental data obtained from the literature promises a novel HTS optoelectronic devices for low-power/ low-noise applications for very high performance communication systems and signal processing.

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