A Submilliwatt Terahertz High-Temperature Superconductive Photomixer Array Source: Analysis and Design

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***Abstract*—A continuous-wave terahertz photomixer array source made of a high-temperature superconductor material is proposed, and its radiation characteristic is studied. Employing photomixer/antenna elements in an array configuration increases the available terahertz power. It is shown that a submilliwatt terahertz power is achievable from a typical array structure. The beam steering capability of the proposed device is also investigated.**

***Index Terms*—Continuous-wave terahertz sources, high-temperature superconductor (HTS), photomixers, terahertz antenna array, terahertz technology.**

I. Introduction

In the past few years, terahertz technology has attracted researchers' attention to its variety of applications including spectroscopy of biological molecules such as DNA and RNA [1], medical imaging and disease diagnostics [2], security issues such as detection of explosive and biological hazards and security screening [3], [4], monitoring and spectroscopy in pharmaceutical industry [5], material spectroscopy and sensing [6], and high data rate short-range communications [7].

Photomixers have been proposed as potentially compact, low cost, low power consuming, coherent, and tunable continuous-wave (CW) terahertz sources [8]–[11]. A terahertz photomixer is a heterodyne scheme, in which two single-mode lasers or the output modes of a dual-mode laser mix in a nonlinear medium, such as a photoconductor [12] or a superconductor [13], to generate a high-frequency signal, whose frequency is equal to the frequency difference of the two lasers or two modes of the dual-mode laser [14], [15]. The frequency of the generated terahertz signal can be tuned over the terahertz frequency range by tuning the central frequency of the lasers.

Recently, the authors have proposed an integrated photomixer/antenna structure as an efficient terahertz source [16], [17]. In a photomixer/antenna element, the generated signal inside the photomixing film radiates simultaneously by designing the film as an efficient radiator. Incorporating a photomixing medium as an antenna element not only eliminates any source-to-antenna coupling problems, but also distributes the optical power over a bigger area and, hence, increases optical power handling capability of the device.

The maximum available power from a single photomixer source is limited by its maximum consumable optical power before device failure. The simple optical excitation scheme in a photomixer/antenna element makes it an ideal element for an array structure. Since there is no need for a feeding network for an array of these elements, one can excite the entire array by two laser beams. One can increase the radiation power by increasing the number of array elements and using higher power lasers. On the other hand, changing the phase distribution of the photocurrent in array elements makes it possible to steer the radiation beam.

In this paper, we introduce an array of high-temperature superconductive (HTS) photomixer/antenna elements as a high-power tunable CW terahertz source. The radiation characteristics of the proposed structure are analyzed and the simulation results for a designed sample are presented.

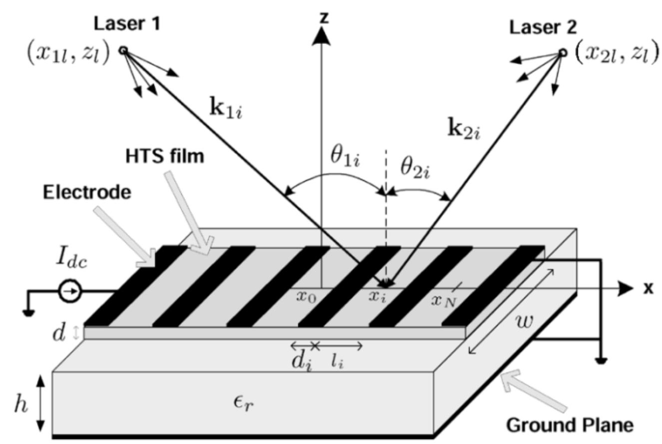

Fig. 1. Superconductive photomixer/antenna array configuration.

II. Formulation

Fig. 1 shows the schematic of an array of HTS photomixer/antenna elements. The array structure consists of an epitaxially grown HTS thin film on a suitable substrate using a growing technique such as molecular beam epitaxy (MBE), sputtering, laser ablation, or metal–organic chemical vapor deposition (MOCVD) [18]. The HTS film can be patterned using standard photolithographic techniques. The electrodes can be printed on

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the HTS film by lift-off techniques followed by an annealing process in an oxygenated environment to reduce the contact resistance and improve the adhesion of the metal pads to the HTS film [19]. The ground plane can be deposited on the back side of the substrate by evaporation or sputtering techniques. A dc current source connected to the electrodes provides a constant bias current for the array elements. One can change the number of array elements by connecting the current source to the appropriate electrode.

Two linearly polarized lasers are located in x–z plane far enough from the surface of the photomixers so that the wave reaching each element can be assumed to be a local plane wave. The corresponding electric field associated with each laser over the ith element can be written as

$$E_{1i} = |E_{1i}| e^{j(\omega_1 t - \mathbf{k}_{1i}\cdot\mathbf{r})} \quad (1)$$
$$E_{2i} = |E_{2i}| e^{j(\omega_2 t - \mathbf{k}_{2i}\cdot\mathbf{r})} \quad (2)$$
$$i = -N, \ldots, N \quad (3)$$

where ω_1 and ω_2 are the angular frequencies of the lasers, $\mathbf{k}_{1i}$ and $\mathbf{k}_{2i}$ are the wave vectors of the lasers over the ith element, and $\mathbf{r}$ is the position vector over the same element.

The wave vectors $\mathbf{k}_{1i}$ and $\mathbf{k}_{2i}$ can be written as

$$\mathbf{k}_{1i} = \frac{(x_i - x_{1l})\hat{x} - z_l\hat{z}}{\left[(x_i - x_{1l})^2 + z_l^2\right]^{1/2}} k_1 \quad (4)$$
$$\mathbf{k}_{2i} = \frac{(x_i - x_{2l})\hat{x} - z_l\hat{z}}{\left[(x_i - x_{2l})^2 + z_l^2\right]^{1/2}} k_2 \quad (5)$$

where k_1 and k_2 are the wave numbers of the lasers in free space.

The incident laser beams interfere inside the elements and create a spatiotemporal grating. The optical power distribution inside the ith element can be written as

$$P_i(\mathbf{r}, t) = P_{0i}(1 - R)[1 + \eta_i \cos(\Omega t - \mathbf{K}_i \cdot \mathbf{r})] e^{\alpha z} \quad (6)$$

where P_{0i} is the total power of the lasers, R is the optical reflectivity, α is the optical absorption coefficient, $0 < \eta_i \leq 1$ is the modulation index or grating contrast, $\Omega = \omega_1 - \omega_2$ is the angular beat frequency, and $\mathbf{K_i} = \mathbf{k}_{1i} - \mathbf{k}_{2i}$ is the grating vector.

The optical power given by (6) is absorbed by the electrons via electron–photon interaction and generates high-energy quasi-particles by breaking Cooper pair bounds and also by exciting low-energy quasi-particles. The resulting high-energy quasi-particles lose their energy via electron–electron and electron–phonon interactions. The absorbed optical power modulates the density of the quasi-particles in time and space. In the presence of a dc bias, the modulated quasi-particles generate a current inside the HTS film, which contains a beat frequency harmonic in its spectrum.

The total equivalent surface current density over the ith element of the array can be written as [13]

$$J_i^s(x, t) = J_{\mathrm{dc}}^s + \Re e\{\tilde{J}_i^s e^{j\Omega t}\} \quad (7)$$

where

$$J_{\mathrm{dc}}^s = \frac{I_{\mathrm{dc}}}{w} \quad (8)$$
$$\tilde{J}_i^s = J_i^s e^{-j[K_{ix}x + \phi_i]} \quad (9)$$

with

$$J_i^s = \left[(J_{1i}^s)^2 + (J_{2i}^s)^2\right]^{1/2} \quad (10)$$
$$K_{ix} = \frac{(x_i - x_{1l})k_1}{\left[(x_i - x_{1l})^2 + z_l^2\right]^{1/2}} - \frac{(x_i - x_{2l})k_2}{\left[(x_i - x_{2l})^2 + z_l^2\right]^{1/2}} \quad (11)$$
$$\phi_i = \tan^{-1}\frac{J_{2i}^s}{J_{1i}^s}. \quad (12)$$

The expressions for J_{1i}^s and J_{2i}^s in terms of the parameters of the HTS photomixer [13] are given in the Appendix.

As it can be seen from (7), the total current inside each element contains a dc component and a traveling-wave terahertz component, where the dc component is equal to the bias current. From an energy conversion point of view, in each element a part of the energy of the exciting lasers is converted to the terahertz signal [13].

Having the current distribution over each element, the far field radiation can be calculated as

$$E_{\theta(\phi)}^i(r, \theta, \phi) = E_{\theta(\phi)}^{\mathrm{hex}} \int_{-w/2}^{w/2} \int_{x_i - l_i/2}^{x_i + l_i/2} J_i^s e^{-j[K_{ix}x + \phi_i]} \times e^{jk_0 \sin\theta [x\cos\phi + y\sin\phi]} dx\, dy. \quad (13)$$

Doing the integration results in

$$E_{\theta(\phi)}^i(r, \theta, \phi) = 4E_{\theta(\phi)}^{\mathrm{hex}} J_i^s e^{-j\phi_i} e^{j[k_0 \sin\theta\cos\phi - K_{ix}]x_i} \times \frac{\sin[l_i/2(k_0\sin\theta\cos\phi - K_{ix})]}{K_{ix} - k_0\sin\theta\cos\phi} \times \frac{\sin[w/2(k_0\sin\theta\sin\phi)]}{k_0\sin\theta\sin\phi} \quad (14)$$

where $E_{\theta(\phi)}^{\mathrm{hex}}$ is the radiated electric field from an x-directed Hertzian electric dipole on a grounded dielectric substrate [20] and k_0 is the free space wave number. The superposition of all these radiated fields is the field produced by the array

$$E_{\theta(\phi)}(r, \theta, \phi) = \sum_{i=-N}^{N} E_{\theta(\phi)}^i(r, \theta, \phi). \quad (15)$$

The total radiated power can be calculated using Poynting's vector theorem [21]

$$P_r = \frac{1}{2\eta} \int_0^{\pi/2} \int_0^{2\pi} [|E_\theta|^2 + |E_\phi|^2] r^2 \sin\theta d\phi\, d\theta \quad (16)$$

where η is the free space impedance.

III. Array Design

The length and the location of the array elements must be chosen judiciously to have maximum radiation for each element

and constructive power combination. From (14), the maximum radiation for the ith element occurs for

$$l_i = \pi / K_{ix} = \lambda_{ix}/2 \tag{17}$$

where λ_{ix} is the photocurrent spatial wavelength along the x axis.

In (17), both l_i and K_{ix} are related to the position of the ith element along the x axis. To find the optimum values for the lengths of the array elements from (17), one has to solve the following iterative equation for x_i:

$$\begin{aligned} x_{\pm i} = x_{\pm(i-1)} &\pm \frac{1}{2} l_{\pm(i-1)} \\ &\pm \frac{3\pi}{2}\left[\frac{(x_{\pm i} - x_{1l})k_1}{[(x_{\pm i} - x_{1l})^2 + z_l^2]^{1/2}}\right. \\ &\left. - \frac{(x_{\pm i} - x_{2l})k_2}{[(x_{\pm i} - x_{2l})^2 + z_l^2]^{1/2}}\right]^{-1} \end{aligned} \tag{18}$$

where $i = 1, \ldots, N, x_0 = 0$, and

$$l_0 = \pi\left[\frac{-x_{1l}}{(x_{1l}^2 + z_l^2)^{1/2}} k_1 + \frac{x_{2l}}{(x_{2l}^2 + z_l^2)^{1/2}} k_2\right]^{-1}. \tag{19}$$

To have a constructive spatial power combining, one has to choose $d_i = l_i$. Once x_i is calculated from (18), one can calculate the lengths of the array elements l_i and their separation distances d_i as

$$\begin{aligned} l_i = d_i = \pi &\left[\frac{(x_i - x_{1l})k_1}{[(x_i - x_{1l})^2 + z_l^2]^{1/2}}\right. \\ &\left. - \frac{(x_i - x_{2l})k_2}{[(x_i - x_{2l})^2 + z_l^2]^{1/2}}\right]^{-1} \end{aligned} \tag{20}$$

where $i = -N, \ldots -1, 1, \ldots, N$.

The thickness of the substrate is determined based on the resonant condition and loss mechanisms of the structure. The best value for the thickness of the substrate to minimize surface mode loss is [22]

$$h = \frac{\pi c}{2\Omega\sqrt{\epsilon_r - 1}}. \tag{21}$$

To have maximum radiation for the entire array, one has to maximize the expression given by (16), which is difficult to do analytically. As we will see in the next section, after designing the array based on the above-mentioned procedure, the maximum radiation can be achieved by a small tuning of the positions of the lasers.

IV. Simulation Results

An array with 61 elements is considered for simulation purpose. The array elements are made of $YBa_2Cu_3O_{7-\delta}$ high-temperature superconductor, which is epitaxially grown on $LaAlO_3$ substrate with relative permittivity of 24. The ground plane is deposited on the back side of the substrate. The thickness and the width of the array elements are 130 nm and 40 μm, respectively. The array elements are biased to a dc current of 23.8 mA. All the physical parameters for a typical $YBa_2Cu_3O_{7-\delta}$ material are presented in Table I.

TABLE I
Physical Parameters of a YBCO-Based Photomixer

Description	Notation	Value
Critical temperature [19]	T_c	87 K
Critical current [19]	I_c	25 mA
Critical current density [19]	J_c	9.6×10^5 A/cm^2
Exponent [23]	γ	1.68
Residual resistance rate [23]	β	10
London penetration depth [23]	$\lambda_L(0)$	220 nm
Optical penetration depth [19]	δ	90 nm
Optical reflectivity [19]	R	0.1
Optical absorption coefficient [24]	α	1.1×10^5cm^{-1}
Electron heat capacity [25]	C_e	0.022 Jcm^{-3}K^{-1}
Phonon heat capacity [19]	C_{ph}	0.85 Jcm^{-3}K^{-1}
Electron thermal conductivity [26]	K_e	0.4 Wm^{-1}K^{-1}
Phonon thermal conductivity [26]	K_{ph}	0.1 Wm^{-1}K^{-1}
Phonon escape time [19]	τ_{es}	12 ns
Electron-phonon relaxation time [23]	$\tau_{e-ph}(T_c)$	3.57×10^{-14} s
Normal state conductivity [23]	$\sigma_n(T_c)$	1.8×10^6 $(\Omega \cdot \mathrm{m})^{-1}$
Quasiparticle diffusion coefficient [27]	D_n	24 cm^2/s
Total electron density [28]	n_0	0.4×10^{22} cm^{-3}

The entire array is excited by two detuned single-mode lasers operating around 532 nm with their frequency difference falling in the terahertz spectrum. Each laser radiates 114 mW optical power, which results in 3.4 mW total absorbed power for each element. The two lasers are located in x–z plane with $x_{2l} = -x_{1l} = 1.3$ mm and $z_l = 50$ mm.

From Fig. 1, the angle between the two lasers can be defined as $\theta_l = \theta_{10} + \theta_{20} = -\tan^{-1}(x_{1l}/z_l) + \tan^{-1}(x_{2l}/z_l)$, which results in $\theta_l = 3^o$ for this specific configuration. The array is designed to work at 3 THz frequency. At this frequency, the optimum value for the thickness of the substrate is 5.21 μm. The length of the array elements and their separation distances are calculated from (18)–(20) (see Fig. 2).

Fig. 3 shows the radiation power versus the angle between the two lasers. As it can be seen from Fig. 3, the optimum value for the angle between the two lasers is $\theta_l = 3.08°$, where the maximum radiation of the entire array happens. Hence, after designing the array for $\theta_l = 3°$, the lasers must be relocated to have $\theta_l = 3.08°$. The radiation power rapidly drops for the angles far from the angle that the array is designed for, since at these angles the maximum radiation condition given by (17) is no longer valid.

Fig. 4 shows the radiation power versus beat frequency for the designed array. It can be seen that about 0.2 mW power is achievable at 3 THz. The bath temperature is $T_0 = 85$ K. Note that upon optical excitation, the temperature of the HTS film increases above the bath temperature. To have the HTS film in its superconducting state, the power of the lasers must be smaller than a critical value [13]. The thickness of the substrate is a function of frequency, which makes the device a narrow-band radiator. Fig. 4 also shows the variation of the radiation power with the thickness of the substrate.

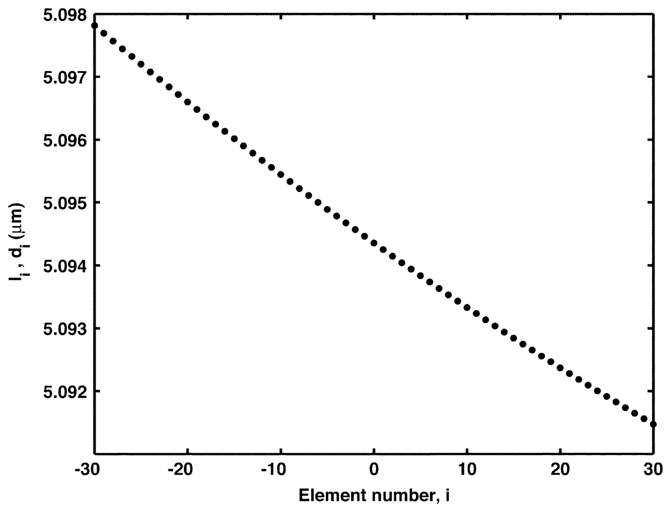

Fig. 2. Lengths of the array elements and their separation distances.

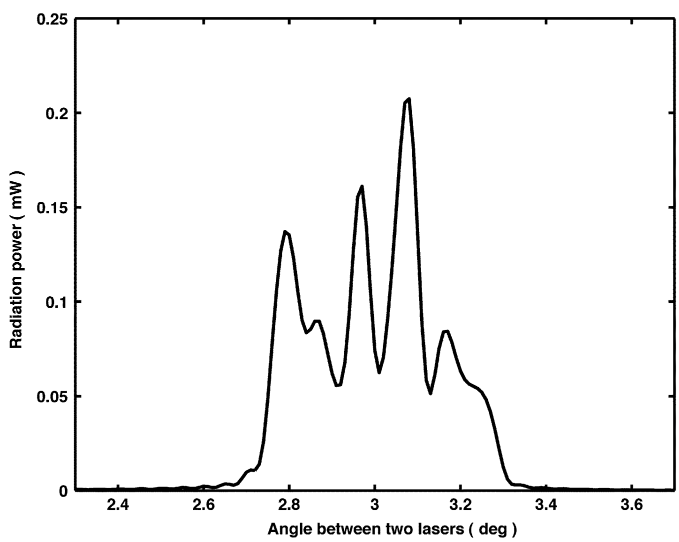

Fig. 3. Radiation power versus angle between two lasers.

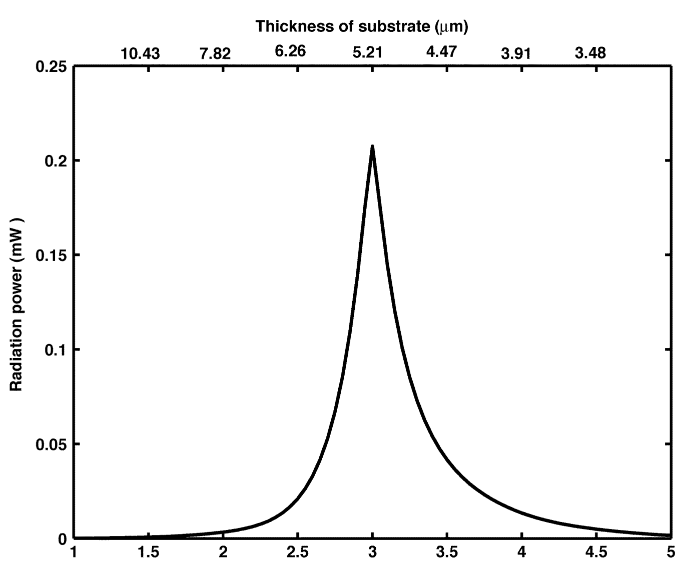

Fig. 4. Terahertz radiation power versus beat frequency for an array designed to operate at 3 THz.

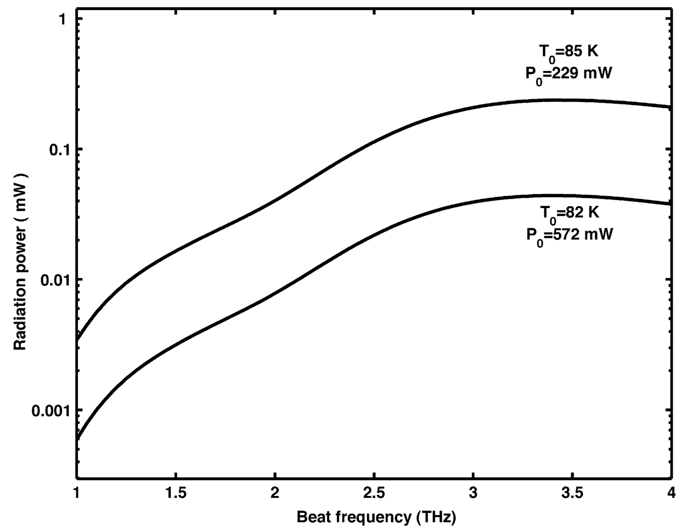

Fig. 5. Total radiation power versus beat frequency at two bath temperatures.

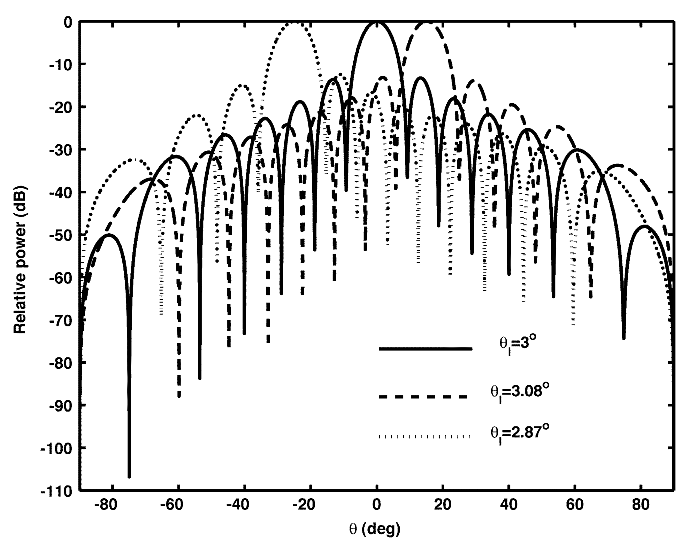

Fig. 6. Radiation pattern of array at $\phi = 0$ plane for different angles between two lasers.

Fig. 5 shows the radiation power versus beat frequency at two different bath temperatures, where the thickness of the substrate is changed according to the beat frequency to have maximum radiation at each frequency. As it can be seen from Fig. 5, the radiation power increases with the beat frequency, the behavior that has been explained by the authors elsewhere [13], and also has been reported by Stevens and Edwards [29]. Fig. 5 also shows that the radiation power is higher for the bath temperatures closer to the critical temperature of the HTS material [13]. The maximum obtainable frequency is limited by the gap frequency of the YBCO sample, which can be from 5 to 30 THz for different samples.

Fig. 6 shows the radiation pattern for different values of θ_l. The array has a narrow beam radiation pattern with -13 dB side-lobe level. It can be seen that by changing the angle between the two lasers, one can steer the radiation beam. The beam steering is due to the change of the grating vector $\mathbf{K_i}$, and consequently change of the current phase distribution over the array elements.

One can increase the terahertz radiation power by using higher power lasers and increasing the number of array elements. The size of an array with 101 elements is 1 mm $\times$ 40 μm. Using two lasers with total optical power of 379 mW, one can achieve 0.44 mW power at 3 THz for an array with 101 elements.

V. Conclusion

A terahertz photomixer/antenna array source made of $YBa_2Cu_3O_{7-\delta}$ thin film has been designed and analyzed. It has been shown that a submilliwatt terahertz power is achievable form a typical array structure. It also has been shown that the radiation beam can be steered more than $\pm 20^\circ$ by changing the angle between the two exiting laser beams. The proposed device is suitable for biological and material spectroscopy, medical imaging, and security applications. It can also be used in heterodyne receivers for radio astronomy and short-range communication applications.

Appendix
Photocurrent Expression in Terms of the Physical Parameters of the Photomixer

The equivalent surface current density can be calculated by integrating the volume current density in an HTS photomixer [13] over the thickness of the HTS film

$$J_{1i}^s = \int_{-d}^{0} [J_{1i}\cos(K_{iz}z) - J_{2i}\sin(K_{iz}z)]\,dz \tag{22}$$

$$J_{2i}^s = \int_{-d}^{0} [J_{1i}\sin(K_{iz}z) + J_{2i}\cos(K_{iz}z)]\,dz \tag{23}$$

where

$$K_{iz} = \frac{-z_l k_1}{[(x_i - x_{1l})^2 + z_l^2]^{1/2}} + \frac{z_l k_2}{[(x_i - x_{2l})^2 + z_l^2]^{1/2}} \tag{24}$$

$$J_{1i} = \frac{\mu_0 \sigma_n^i \tau_{e-ph,i} \Omega^2 \lambda_L^2(0)}{1 + \Omega^2 \tau_{e-ph,i}^2} \frac{\gamma \hat{T}_{\mathrm{ac},i}^e (\hat{T}_{\mathrm{dc},i}^e)^{2\gamma - 1}}{[1 - (\hat{T}_{\mathrm{dc},i}^e)^\gamma]^2} J_0 \tag{25}$$

$$J_{2i} = -\frac{\mu_0 \sigma_n^i \Omega \lambda_L^2(0)}{1 + \Omega^2 \tau_{e-ph,i}^2} \frac{\gamma \hat{T}_{\mathrm{ac},i}^e (\hat{T}_{\mathrm{dc},i}^e)^{2\gamma - 1}}{[1 - (\hat{T}_{\mathrm{dc},i}^e)^\gamma]^2} J_0 + e n_0 \gamma D_n K_{ix} (\hat{T}_{\mathrm{dc},i}^e)^{\gamma - 1} \hat{T}_{\mathrm{ac},i}^e \tag{26}$$

$$J_0 = J_{\mathrm{dc}} \left[1 + \frac{\mu_0 \sigma_n^i \tau_{e-ph,i} \Omega^2 \lambda_L^2(0)}{2[1 + \Omega^2 \tau_{e-ph,i}^2]} \times \left(\frac{\gamma (\hat{T}_{\mathrm{dc},i}^e)^\gamma \hat{T}_{\mathrm{ac},i}^e}{1 - (\hat{T}_{\mathrm{dc},i}^e)^\gamma} \right)^2 \right]^{-1} \tag{27}$$

in which

$$\tau_{e-ph,i} = \tau_{e-ph}(T_c) \frac{1 + \beta[(\hat{T}_{\mathrm{dc},i}^{ph})^{1-\gamma} - \hat{T}_{\mathrm{dc},i}^{ph}]}{\hat{T}_{\mathrm{dc},i}^{ph}} \tag{28}$$

$$\hat{T}_{\mathrm{dc},i}^{ph} = \hat{T}_0 + \frac{P_0(1-R)}{V_i T_c} \frac{1}{G_{ph}} e^{\alpha z} \tag{29}$$

$$\hat{T}_{\mathrm{dc},i}^{e} = \hat{T}_0 + \frac{P_0(1-R)}{V_i T_c} \left(\frac{1}{G_{ph}} + \frac{1}{G_{e-ph,i}} \right) e^{\alpha z} \tag{30}$$

$$\hat{T}_{\mathrm{ac},i}^{e} = \frac{\eta_i P_0(1-R)}{V_i T_c \Omega C_e} \left(\frac{C_e^2 + \Omega^2 C_{ph}^2 \tau_{e-ph,i}^2}{(C_e + C_{ph})^2 + \Omega^2 C_{ph}^2 \tau_{e-ph,i}^2} \right)^{1/2} \times e^{\alpha z} \tag{31}$$

where $\sigma_n^i = n_0 e^2 \tau_{e-ph,i}/m$ is the normal conductivity of the ith element, $\lambda_L(0)$ is the London penetration depth at zero temperature, γ is an exponent, e is the electron charge, n_0 is the total electron density, D_n is the quasi-particle diffusion coefficient, $J_{\mathrm{dc}} = I_{\mathrm{dc}}/wd$ is the dc bias current density, $\tau_{e-ph}(T_c)$ is the momentum relaxation time at the critical temperature, β is the residual resistance rate, V_i is volume of the ith element, T_c is the critical temperature, $G_{ph} = C_{ph}/\tau_{es}$ is the phonon mismatch coefficient, $G_{e-ph,i} = C_e/\tau_{e-ph,i}$ is the electron–phonon coupling coefficient of the ith element, and $\hat{T}_0$ is the reduced bath temperature.

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