Photothermal Modeling and Analysis of Intrabody Terahertz Nanoscale Communication

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***Abstract*— Wireless communication among implanted nano-biosensors will enable transformative smart health monitoring and diagnosis systems. The state of the art of nano-electronics and nano-photonics points to the terahertz (THz) band (0.1–10 THz) and optical frequency bands (infrared, 30–400 THz, and visible, 400–750 THz) as the frequency range for communication among nano-biosensors. Recently, several propagation models have been developed to study and assess the feasibility of intra-body electromagnetic (EM) nanoscale communication. These works have been mainly focused on understanding the propagation of EM signals through biological media, but do not capture the resulting photothermal effects and their impact both on the communication as well as on the body itself. In this paper, a novel thermal noise model for intra-body communication based on the diffusive heat flow theory is developed. In particular, an analytical framework is presented to illustrate how molecules in the human body absorb energy from EM fields and subsequently release this energy as heat to their immediate surroundings. As a result, a change in temperature is witnessed from which the molecular absorption noise can be computed. Such analysis has a dual benefit from a health as well as a communication perspective. For the medical community, the presented methodology allows the quantization of the temperature increase resulting from THz frequency absorption. For communication purposes, the complete understanding of the intra-body medium opens the door toward developing modulations suited for the capabilities of nano-machines and tailored to the peculiarities of the THz band channel as well as the optical window.**

***Index Terms*— Photo-thermal, nano-networks, wireless nanosensor networks, terahertz, optical, molecular absorption noise.**

I. Introduction

NANOTECHNOLOGY is facilitating the advancements of novel nanosensors that are able to detect several types of events at the nanoscale with unprecedented accuracy. In-vivo nanosensing systems, which have the potential to operate inside the human body in real time, have been recently proposed as a technique to provide faster and more precise disease diagnosis and treatment in comparison to traditional technologies [1], [2]. In the current time, researchers have effectively deployed surface plasmon resonance sensors to investigate circulating biomarkers in body fluids for the diagnosis of deadly diseases, ranging from cardiovascular ones to various types of cancer [3], [4].

By means of communication, nanosensors will be able to autonomously transmit their sensing information to a common sink, be controlled from a command center, or coordinate joint actions when needed [5]. The state of the art of nano-electronics and nano-photonics points to the Terahertz (THz) band (0.1-10 THz) and the optical frequency bands (infrared, 30-400 THz, and visible, 400-750 THz) as the frequency range for communication among nano-biosensors. Among others, plasmonic nano-lasers with sub-micrometric footprint [6], THz signal sources [7], plasmonic nano-antennas for optical [8] and THz frequencies [9], and single-photon detectors with unrivaled sensitivity [10] have already been developed.

The study of THz propagation within the human body is still at its infancy though most nano-biosensing applications rely on the use of light. A genuine model that accounts for the intra-body signal degradation has been recently presented in [11]. However, as the propagation of THz band waves inside the human body is drastically impacted by the absorption of liquid water molecules [12], Guo *et al.* [13] advocated the use of the optical window for intra-body wireless communication among nanosensors with plasmonic nano-antennas. The reason behind this is the minimal absorption from liquid water molecules in the so called optical window, roughly between 400 THz and 750 THz [14]. In addition, optical frequencies have already been used in many in-vivo applications [15].

Molecular absorption is a phenomenon that not only compromises the propagation of electromagnetic (EM) signals in the body, but it can also result in photothermal damage to the biological entities in the system. Due to the EM radiation of nano-antennas, the human body particles will seize part of the EM energy. As a result, the absorbed power will activate the vibration of the particles thereby resulting in heat generation and temperature increase. This thermal effect will then be converted into noise by defining the transmission bandwidth. In fact, noise stimulated by molecular absorption has been first explored by Jornet *et al.* [10]. Later, a comprehensive study

Manuscript received April 21, 2017; revised August 22, 2017; accepted September 22, 2017. Date of publication September 28, 2017; date of current version January 18, 2018. This work was supported in part by the Information and Communications Technology Fund in UAE and in part by the U.S. National Science Foundation under Grant CBET-1445934 and Grant CBET-1555720. *(Corresponding author: Raed M. Shubair)*

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Digital Object Identifier 10.1109/TNB.2017.2757906

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on noise in higher frequency bands has been presented in [16]. In the context of intra-body communication, few works exist in the literature [17], [18] that investigate molecular absorption noise; however, this is the first work which tackles intra-body noise from the diffusive heat flow perspective.

In this paper, we model and analyze the photothermal effects created by intra-body wireless communication at THz frequencies. In particular, a mathematical framework based on the heat diffusion model is developed to characterize how molecules in the human body absorb energy from EM fields and subsequently release this energy as heat to their immediate surroundings. Thus, a change in temperature is observed from which the molecular absorption noise can be calculated. In addition, the effect of both the power of the EM source as well as the heating exposure time on the temperature rise are numerically investigated by means of finite element methods and utilizing COMSOL Multi-physics. On the one hand, from a medical perspective, evaluating the temperature increase resulting from THz intra-body molecular absorption allows health-safety assessment. On the other hand, from a communication viewpoint, the calculation of the molecular absorption noise is a necessary step towards analyzing the feasibility of intra-body nanoscale communications and a key aspect to take into account in the design of communication strategies (namely, modulation and coding techniques) suited to this new paradigm. Actually, the developed model is a necessary step towards fully characterizing the intra-body channel model.

The rest of the paper is organized as follows. In Sec. II, molecular absorption by the human body is discussed. In Sec. III, intra-body heat flow analysis is formulated using both single as well as multiple particle analysis. In Sec. IV, the numerical results are illustrated and supported by EM wave propagation simulation. Finally, we draw our conclusions in Sec. V.

II. Molecular Absorption in the Human Body

Molecules present in a standard medium are excited by EM waves at specific frequencies within the THz band and the optical window. An excited molecule internally vibrates, i.e., its atoms show periodic motion, while the molecule as a whole has constant translational and rotational motions. It must be noted that both the THz and optical waves are non-ionizing, i.e., they induce vibration, but cannot break molecules. Due to this vibration, part of the energy of the propagating wave is converted into kinetic energy or, from the communication perspective, simply lost [10]. Hence, molecular absorption is calculated by computing the fraction of the incident EM radiation that is able to pass through the medium at a given frequency. Using the Beer-Lambert law [19], attenuation due to molecular absorption for an EM traveling wave at a distance, d, is given by

$$L_{abs} = e^{-\mu_{abs} d}, \tag{1}$$

where μ_{abs} is the molecular absorption coefficient. This coefficient depends on the composition of the medium [19].

In the context of intra-body communications, the same approach is followed since the body is composed of nanoscale biomolecular structures. These include chromophores, which are compounds in our tissues responsible for absorbing light radiation. Each molecule has a spectrum of absorption that can quickly change even for small wavelength variations. The disruption of the medium optical uniformity can be expressed in the non-uniformity of the refractive index throughout the medium [20]. The molecular absorption coefficient can be calculated using

$$\mu_{abs} = \frac{4\pi n''}{\lambda_g}, \tag{2}$$

where λ_g, the effective wavelength, is λ/n', n' and n'' are the real and imaginary parts of the tissue refractive index n, respectively, i.e.,

$$n = n' - jn''. \tag{3}$$

Moreover, the refractive index is related to the relative permittivity (dielectric constant) ϵ_r of a material by $n = \sqrt{\mu_r \epsilon_r}$, where μ_r is the relative permeability of the material and is considered to be equal to one for biological tissues since they are non-magnetic at our frequencies of interest [21]. By calculating the molecular absorption coefficient, the path loss experienced as the THz wave propagates through the human tissues can be calculated. Elayan *et al.* [22] present simulation results that capture both the molecular absorption level as well as the total path loss at both the THz band as well as the optical window.

III. Intra-Body Heat Flow Analysis

Our system of interest is composed of a medium full of both biological cells as well as liquid-surrounded heat sources larger than tens of nanometers (nm). The heat sources in this work are considered to be nano-antennas in nano-bio-sensing implants in the human body. As these nano-antennas radiate EM waves, cells will capture part of this EM energy through the process of molecular absorption. Hence, subsequent to such exposure, the cells also become heat sources. Consequently, the absorbed EM energy will be converted into heat which will result in temperature increase around the cells. Therefore, the objective of our study is to analyze and quantify such temperature increase as a function of the EM wave power as well as the duration of the irradiation process. Both the maximum temperature increase for a given current as well as the total temperature increase in the medium are going to be computed.

Throughout this paper, we will use the general term "particle" to refer to both the biological cells and the nano-antennas. Moreover, we adopt a model that assumes a homogeneous medium of identical particles. Note that a biological tissue is an ensemble of similar cells having the same origin, where together with other tissues, it forms an organ. In intra-body communications, the EM wave will pass through a structured layer of different tissues, namely, the organ (e.g., the skin which contains different layers). Therefore, to find out the EM intensity in each layer, the need for a non-homogeneous model is clear [13]; however, once the EM intensity is given in a specific region (tissue), then the homogeneous assumption for the heat flow analysis can be adopted.

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The generation of heat due to the absorption of EM energy results in a temperature increase that will be analyzed for both single as well as multiple particles. The diffusive heat flow equation for a homogeneous medium is given by [23]

$$k(r)\nabla^2 T(r,t) + q(r,t) = \rho(r)C_p(r)\frac{\partial T(r,t)}{\partial t}, \tag{4}$$

where r and t are the radial distance and the time at which the temperature, $T(r,t)$, is computed. $k(r)$ is the particle thermal conductivity, $\rho(r)$ is the particle density, and $C_p(r)$ is the particle specific heat capacity. In (4), $q(r,t)$ represents the rate of the generated heat energy per unit volume. Physically, $q(r,t)$ can be viewed as the energy source formed due to EM absorption in the particles and is given by [24], [25]

$$\begin{aligned} q(r,t) &= \langle \mathbf{J}(r,t)\cdot\mathbf{E}(r,t)\rangle_t \\ &= -\frac{1}{2}\mathbf{Re}\left[j\omega\frac{\epsilon(r,t)-1}{4\pi}\tilde{\mathbf{E}}(r,t)\tilde{\mathbf{E}}^*(r,t)\right]. \end{aligned} \tag{5}$$

Using the time-average operator indicates that to express the correlation of fluctuations in the diffusive heat flow equation, we should refer to the average value of the function over a given time range [26]. In (5), $\mathbf{J}(r,t)$ is the current density, $\mathbf{E}(r,t) = \mathbf{Re}[\tilde{\mathbf{E}}(r,t)\cdot e^{-jwt}]$ is the resulting electric field in the system, $\epsilon(r,t)$ is the dielectric constant of the medium, $j = \sqrt{-1}$, and $\omega = 2\pi f$ is the angular frequency. Here, we assume that the system is excited with an external nano-antenna field $\mathbf{E}_0(t) = \mathbf{Re}[\tilde{\mathbf{E}}_0(t)\cdot e^{-jwt}]$. The heat model is developed for a medium characterized by, $\epsilon(r,t) = \epsilon_p$ inside the particle and $\epsilon(r,t) = \epsilon_0$ elsewhere. If the antenna radiates at $t = 0$, its intensity is given by $I(t) = I_0 = c{\mathbf{E_0}}^2\sqrt{\epsilon_0}/8\pi$ for $t > 0$ and 0 at $t < 0$, where c is the speed of light in vacuum and ϵ_0 is the dielectric constant of the medium.

A. Single Particle Analysis

By solving (4) in the case of having a single particle in the origin of coordinates ($r = 0$), the temperature at distances larger than the radius of the particle is given by [27],

$$T(r) = T_{avg} + \frac{Q}{4\pi k_0 r}, \quad (r > a), \tag{6}$$

where k_0 is the thermal conductivity of the medium, r is the distance from the center of a particle, and a is the particle radius. Q is the total amount of heat production given as [27]

$$Q = qV_p, \tag{7}$$

where V_p is the particle volume. Knowing that $\tilde{\mathbf{E}} = (3\epsilon_0/(2\epsilon_0+\epsilon_p))\mathbf{E_0}$, q in (7) can be written as [27]

$$q = -\mathbf{Re}\left[j\omega\frac{\epsilon(r)-1}{8\pi}\mathbf{E}_0^2\left|\frac{3\epsilon_0}{2\epsilon_0+\epsilon_p}\right|^2\right], \tag{8}$$

Hence, (8) can be re-written as [27]

$$q = \frac{\omega}{8\pi}E_0^2\left|\frac{3\epsilon_0}{2\epsilon_0+\epsilon_p}\right|^2\epsilon_p'', \tag{9}$$

where ϵ_p'' is the imaginary component of the particle dielectric constant. Importantly, the temperature, T_{avg}, is created by all other particles in the region of interest.

The maximum temperature increase occurs at ($r = a$) and is given as

$$\triangle T_{max} = T_{max} - T_{avg} = \frac{Q}{4\pi k_0 a}. \tag{10}$$

Substituting (7) and (9) in (10), we have [25]

$$\triangle T_{max}(I_0) = \frac{a^2}{3k_0}\frac{\omega}{8\pi}\left|\frac{3\epsilon_0}{2\epsilon_0+\epsilon_p}\right|^2\epsilon_p''\frac{8\pi I_0}{c\sqrt{\epsilon_0}}. \tag{11}$$

Now that the maximum temperature increase for a given current has been computed, the total temperature increase in the medium is going to be calculated to fulfill our analysis. By the conservation of energy, the total amount of heat production Q is divided into, Q_{in}, which represents the heat generated by the particle and, Q_{out}, which represents the heat dissipated by the particle. The former is given by

$$Q_{in} = \sigma_{abs} I_0 V_p, \tag{12}$$

where I_0 is the light intensity and σ_{abs} is the particle absorption cross section which can be calculated as $\mu_{abs} = (N_0/V_0)\sigma_{abs}$ where N_0 is the number of the cells in volume V_0 and μ_{abs} is the molecular absorption defined in equation (2). From here, one can stem the relationship between the thermal and molecular absorption perspectives of the model. Also, Q_{out} is represented as

$$Q_{out} = -4\pi r^2 k_{eff}\frac{dT}{dr} = 4\pi r k_{eff}\Delta T, \tag{13}$$

in which $k_{eff} = \frac{k_0+k}{2}$. Since the amount of heat generated is equivalent to amount of heat dissipated, the change in temperature the surface of a particle experiences can be found by equating Q_{in} and Q_{out}. Therefore, the total temperature increase, $\triangle T$, encountered at the surface is given as

$$\triangle T = \frac{\sigma_{abs} I_0 V_p}{4\pi r k_{eff}}. \tag{14}$$

Further inspection of (4) provides the capability of extracting the characteristic time scale expected relevant for nanoscale dimensions. Such scale represents the time needed for the thermal fields from neighboring particles to overlap [28]. In order to do so, the volume outside the particle is considered where the heat sources are equal to zero ($q = 0$). In this case, (4) becomes

$$\frac{\partial T(r,t)}{\partial t} - \alpha\nabla^2 T(r,t) = 0, \tag{15}$$

where $\alpha = k/\rho C_p$ is the thermal diffusivity. As the name implies, the thermal diffusivity can be viewed as a measure of the rate at which heat diffuses through the material. When a thermal perturbation is applied at some point in a medium (e.g., an instantaneous change in a surface temperature), it generally takes on the order of $\tilde{t}$ for the perturbation to appear at a distance from the particle [29]. Thus, the time scale related to the thermal process, $\tilde{t}$, is [28]

$$\tilde{t} = d_{pp}^2/\alpha. \tag{16}$$

where d_{pp} is the average particle-particle separation.

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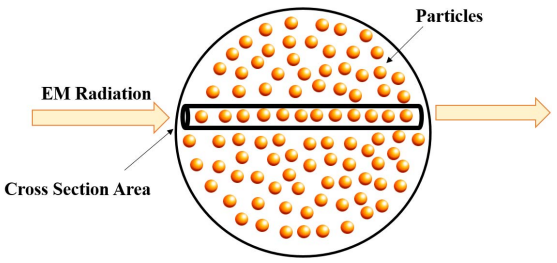

Fig. 1. System of an ensemble of particles surrounded by a medium.

B. Multiple Particle Analysis

When considering the heat generation from an assembly of particles in close proximity, as can be seen in Fig. 1, the problem becomes more complex. In this case, the temperature increase, ΔT_{tot}, will stem from both self-contribution, ΔT_s, as well as external contributions, ΔT_{ext}. It is to be noted that ΔT_s is equivalent to ΔT_{max} given in (10), as it refers to the maximum temperature increase experienced by the source particle or the "self-contribution". The latter contribution results from the heat delivered by the other $N_p - 1$ particles located at $\mathbf{r_m}$ from a reference particle $\mathbf{r_n}$, and can be expressed as [30]

$$\Delta T_{ext} = \sum_{\substack{m=0 \\ m \neq n}}^{N_p} \frac{Q_m}{4\pi k_{eff}} \frac{1}{|\mathbf{r_n} - \mathbf{r_m}|}, \tag{17}$$

where the coefficient, Q_m, describes the heat produced by the N_p particles and each particle is treated as a point-like source of heat. Hence, the total temperature increase is

$$\Delta T_{tot} = \Delta T_s + \Delta T_{ext}. \tag{18}$$

In order to develop an expression for the collective temperature increase, ΔT_{ext}, we follow an approach similar to the one presented in [24]. To carry out the derivation, an array of identical particles ($Q_m = Q_0$) extending over a circular area of diameter, D, and a unit cell area, A, is considered. The differential heat power delivered by an elementary area $dxdy$, located at the position (x, y), is

$$d^2Q(x, y) = Q_0 \frac{dxdy}{A}. \tag{19}$$

This delivered power contributes to a temperature increase at the centre of the array in line with (6)

$$d^2T(x, y) = \frac{d^2Q(x, y)}{4\pi k_{eff}\sqrt{x^2 + y^2}}, \tag{20}$$

$$d^2T(x, y) = \frac{Q_0 dxdy}{4\pi k_{eff} A\sqrt{x^2 + y^2}}. \tag{21}$$

By noticing that $dxdy = \sqrt{x^2 + y^2} drd\theta$, the total temperature increase is given by

$$\Delta T_{ext} = \int_0^{2\pi} \int_0^{D/2} \frac{Q_0}{4\pi k_{eff} A} drd\theta. \tag{22}$$

It must be noted that ΔT_{ext} excludes the contribution of the source itself. Therefore, the limits must be interchanged where the integral will run over the distance from $\sqrt{A/\pi}$ instead of 0 in order to omit the contribution of the source area, which yields

$$\Delta T_{ext} = \frac{Q_0}{2\pi k_{eff}\sqrt{\frac{A}{\pi}}} \left(1 - \frac{2\sqrt{A}}{\sqrt{\pi} D}\right). \tag{23}$$

In addition, various expressions of ΔT_{ext} exist depending on the typical array geometry and various illumination conditions. In general, these formulas follow Govoro's general trend found in [24] which provide an estimate for the total temperature increase under various system structures.

C. Intra-Body Molecular Absorption Noise Analysis

An increase in the temperature of the medium results in an increase in the emissivity of the channel and, ultimately, a higher molecular absorption noise power [10]. To compute the equivalent noise power at the receiver, it is necessary to define the transmission bandwidth, which depends on the transmission distance and the composition of the medium. For a given bandwidth, B, the molecular absorption power at the receiver can be calculated as

$$P_n(f, d) = \int_B S_N(f, d) df = k_B \int_B \Delta T_{tot}(f, r) df, \tag{24}$$

where f stands for frequency, r is the transmission distance, S_N refers to the noise power spectral density (p.s.d), k_B is the Boltzmann constant and ΔT_{tot} refers to the equivalent noise temperature given by (18).

Taking into account that the computation of the thermal noise power would require the definition of the usable bandwidth, B, the noise temperature is calculated instead as will be indicated in the subsequent section.

IV. Numerical Results

In this section, we numerically study the impact of different system parameters on the generated heat and noise. More specifically, on the one hand, MATLAB is utilized to evaluate the equations developed in Sec. III and calculate the total temperature increase experienced when performing both the single as well as multiple particle analysis. On the other hand, EM simulations were conducted via COMSOL Multi-physics in order to compute the effect of the power of the EM source as well as the heating exposure time on the temperature rise.

Despite the fact that our analysis is valid for any homogeneous medium, in this section we provide numerical results for the specific case of blood, as a good example of a medium with various components. Blood plasma is the liquid component of the blood and is a mixture of mostly water (up to 95% by volume) and tiny particles of dissolved protein, glucose, and minerals, among others. It also holds different types of blood cells in suspension, which are considered as the larger particles of the blood, namely, platelets (2 μm in diameter), red blood cells (7 μm), and white blood cell (up to 20 μm). Particularly, we consider red blood cells and utilize realistic parameters of the intra-body properties as summarized in Table I. As mentioned in Sec. III, the primary energy source in the system is a nano-antenna, which radiates an EM wave at a distance. As a result of the absorption, cells become heat sources.

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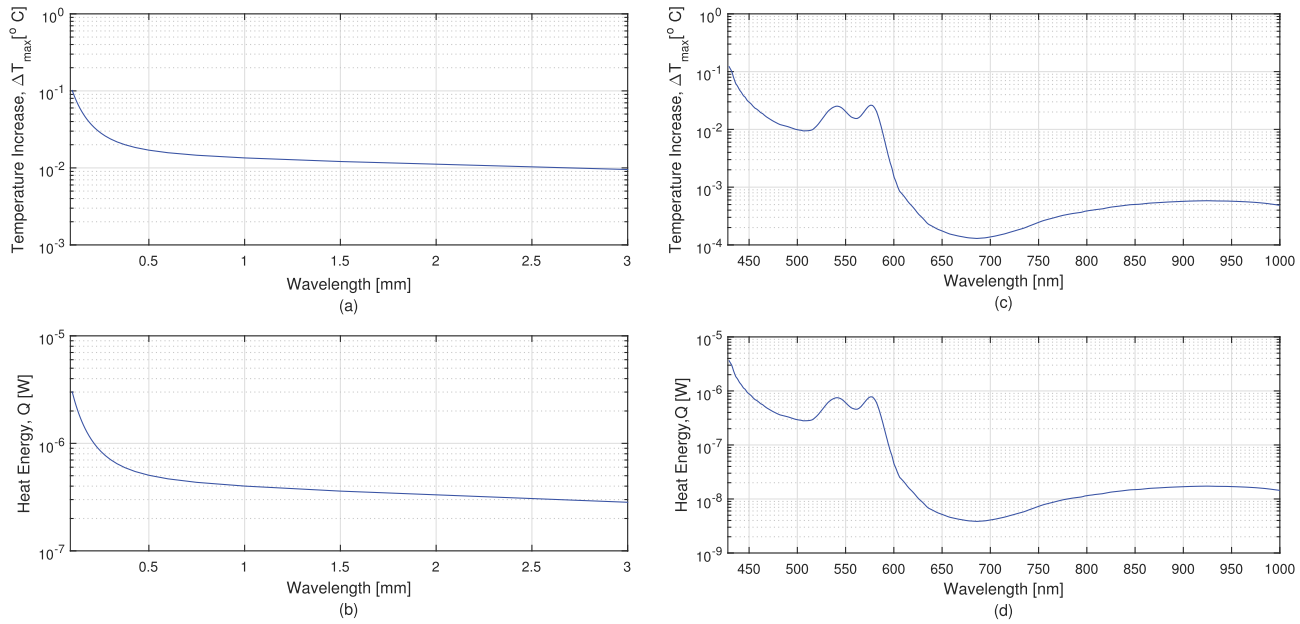

Fig. 2. (a) Temperature increase at the surface of red blood cell due to light dissipation at THz wavelengths, (30 μm$-$3 mm). (b) total heat at the surface of a red blood cell due to light dissipation at THz wavelengths, (30 μm$-$3 mm). (c) temperature increase at the surface of red blood cell due to light dissipation at optical wavelengths, (400 nm$-$1 μm). (d) total heat at the surface of a red blood cell due to light dissipation at optical wavelengths, (400 nm$-$1 μm).

TABLE I
SIMULATION PARAMETERS [31]–[33]

Parameter	Symbol	Value	Unit
Red blood cell thermal conductivity	k_p	0.52	W/m/^{o}C
Red blood density	ρ	1025	kg/m^3
Red blood cell specific heat capacity	C_p	3617	J/kg/^{o}C
Red blood cell radius	a	4×10^{-6}	m
Blood plasma thermal conductivity	k_0	0.58	W/m/^{o}C
Light Intensity	I_0	10^4	W/cm^2

A. Single Particle

Fig. 2 (a) shows the temperature increase a single red blood cell experiences due to light dissipation at THz frequencies, whereas Fig. 2 (b) illustrates the thermal energy generated at the surface of the cell. Moreover, Fig. 2 (c) and Fig. 2 (d) illustrate the same phenomena at optical frequencies. The figures indicate that both the temperature increase and the thermal energy generated are minimal. It can be also realized that such thermodynamic metrics depend on the physical properties of the particle. In particular, the imaginary part of the dielectric constant plays an important role as indicated by (9) and (11). In addition, if the particle size is sufficiently large, the temperature increase becomes noticeable since both the heat and temperature rely in their computation on the particle radius.

B. Multiple Particle

Fig. 3 (a) and Fig. 3 (b) provide the temperature increase experienced by multiple red blood cells. Such accumulative effect arises from the addition of heat fluxes generated by the single particles. The more the particles, the stronger the temperature increase that appears in the system. It is evident that for smaller inter-particle distances, the interaction between the temperature fields is stronger; the reason behind this is that the time needed for thermal fields from neighboring particles to overlap is shorter for smaller particle-particle separation. In Fig. 4, we plot the heating time, $\tilde{t}$, given in (16) versus the particle-particle separation. Recall that from Sec. III-A, $\tilde{t}$ refers to the time needed for the thermal fields from neighboring particles to overlap. It is evident that as this separation increases, the heating time required also increases. Such observation verifies the decaying temperature curve attained in Fig. 3 (a) and Fig. 3 (b). It can also be noticed that the temperature increase experienced at THz is higher than that at optical frequencies, which can be stemmed from the fact that the absorption effect is higher at the former frequency range.

C. COMSOL Simulation

In order to complement the mathematical model presented in Sec. III, an analogous model has been constructed using COMSOL Multiphysics. In fact, one of the critical features that distinguishes this software is its bio-heat interface which is considered a convenient tool for simulating thermal effects in human tissues and other biological systems.

The model we developed consists of a red blood cell suspended in a liquid medium. The thermal parameters used in COMSOL are analogues to those used in MATLAB and presented in Table I. Both EM as well as time-dependent bio-heat studies were applied to the constructed model, having a wavelength of 600 nm (500 THz). A point dipole has been used as the heating source as shown in Fig. 5.

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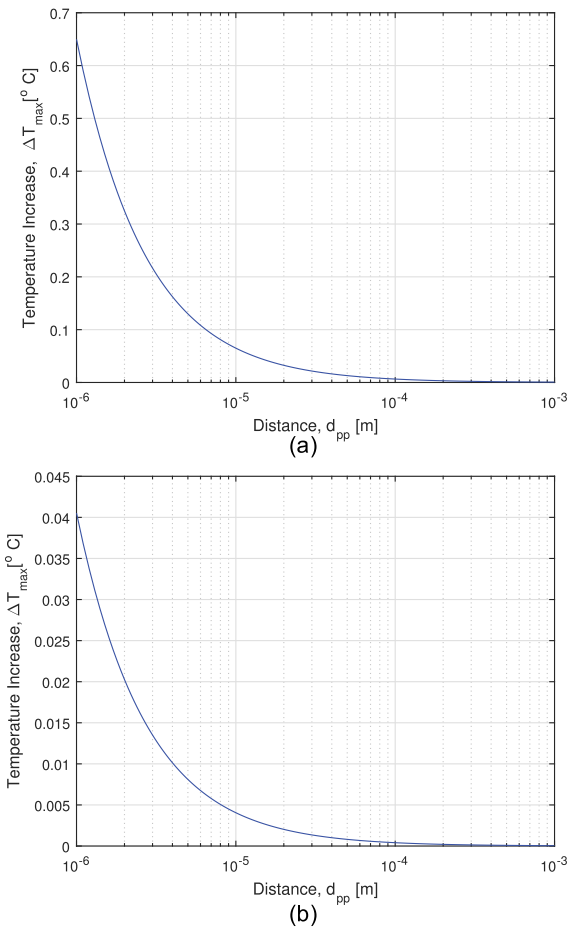

Fig. 3. (a) Temperature increase due to the collective heating of 1000 red blood cells at 1 THz (300 μm). (b) temperature increase due to the collective heating of 1000 red blood cells at 500 THz (600 nm).

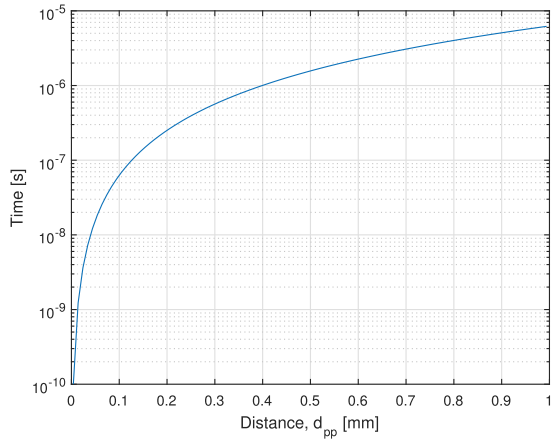

Fig. 4. Time scale for heat diffusion of a single particle.

Fig. 5 (a) shows the electric field intensity of a single red blood cell. Fig. 5 (b) shows the generated heat in the cell due the presence of EM wave radiation. It can be seen from this figure that the cell gets heated up mostly in the center since it consists of hemoglobin which absorbs more energy than plasma [34]. The electric field continues to have a high concentration even at a distance after the cell; however, it will not change the temperature of the plasma significantly. Specifically, Fig. 5 (b) provides a visualization of the developed model via COMSOL in which the temperature changes throughout a cell exposed to a EM wave radiation of 10 ms. It can be noticed that the cell starts to heat up from the side the antenna radiates through it, and then the cell itself turns into a heat source and dissipates the heat to the medium. This finding is further verified in Fig. 6 (a), where the temperature variation at the cell center is the highest in comparison to the cell membrane and to that between the cell and the antenna.

In COMSOL, the dipole moment, $I_0 l$, is set to 1 mA· m. The electric field intensity from an antenna depends on the current distribution as well as the geometry of the radiating antenna. In the case of a half wavelength (dipole) antenna, the electric field is given by

$$E_\theta(r) = j60 I_0 \frac{e^{-jk_c r}}{r} \frac{\mathbf{cos}(\frac{\pi}{2}\mathbf{cos}\theta)}{\mathbf{sin}\theta}, \tag{25}$$

where θ is the angle between the antenna axis and the vector to the observation point, I_0 is the peak current at the feed-point, r is the distance to the antenna, and k_c is the complex propagation constant given by $\omega\sqrt{\mu\epsilon_c} = \beta - j\alpha$, where $\epsilon_c = \epsilon - j\frac{\sigma}{w}$. In the latter expression, ϵ and σ represent the permittivity and conductivity of the human tissue medium surrounding the dipole antenna. When the antenna is viewed broadside ($\theta = \frac{\pi}{2}$), the electric field is maximum and is given by

$$|E_\theta(r)|_{\theta=\frac{\pi}{2}} = 60\frac{I_0}{r}. \tag{26}$$

Solving (26) for the peak current yields

$$I_0 = \frac{1}{60} r\, |E_\theta(r)|_{\theta=\frac{\pi}{2}}\,. \tag{27}$$

The average power radiated by the antenna is

$$P_{avg} = \frac{1}{2} R_{rad} I_0^2, \tag{28}$$

where R_{rad} is the the center-fed half wave antenna's radiation resistance. Substituting (27) in (28) and solving for the maximum electric field yields

$$|E_\theta(r)|_{\theta=\frac{\pi}{2}} = \frac{120}{r}\sqrt{\frac{P_{avg}}{2R_{rad}}}. \tag{29}$$

On the other hand, for a short dipole $l \ll \lambda$, the current distribution is nearly triangular. In this case, the electric field and radiation resistance are given as

$$E_\theta(r) = j60\pi I_0 \frac{l}{\lambda}\frac{e^{-jk_c r}}{r}\mathbf{sin}\theta, \tag{30}$$

$$R_{rad} = 20\pi^2 \left(\frac{l}{\lambda}\right)^2. \tag{31}$$

Although the pulse duration utilized in this case is 10 ms, still the temperature increase is only 0.55°C. In fact, such exposure time may be further increased and used for therapeutic applications including hyperthermia, which is utilized for localized cancer treatment without impacting the surrounding normal tissues [35]. In addition, by further increasing the signal strength of the point dipole, elevation in the temperature is witnessed as indicated in Fig. 6 (b).

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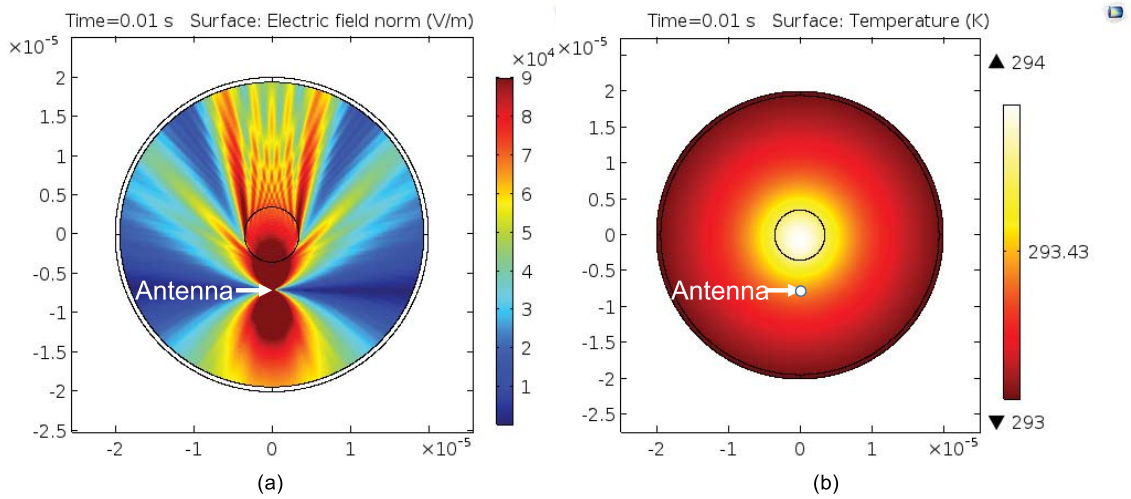

Fig. 5. A single red blood cell exposed to an EM wave with the duration of 10 ms and a dipole moment of 1 mA · m. (a) electric field intensity (b) generated heat.

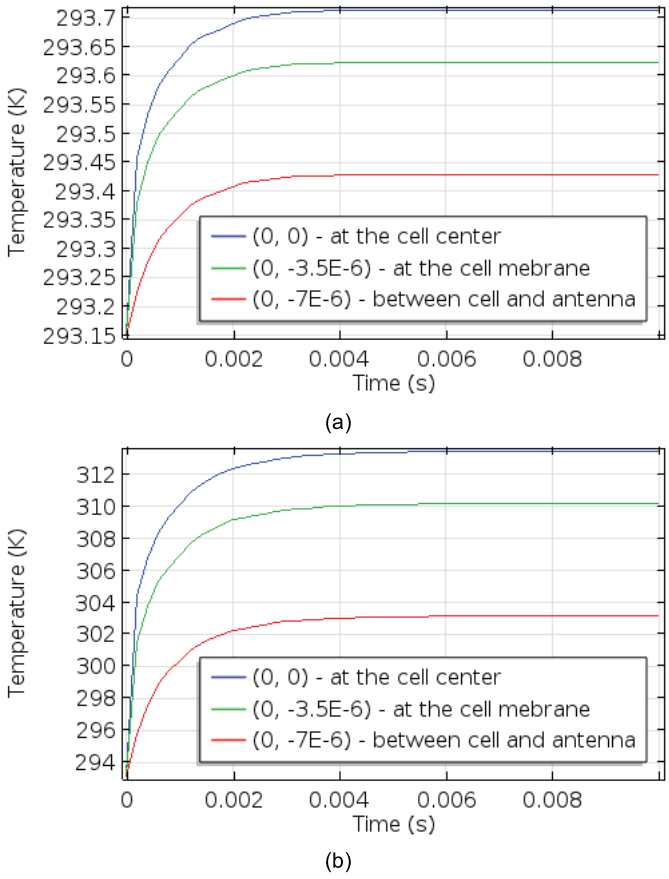

Fig. 6. The temperature variation as a function of time experienced at the cell center, at the cell membrane and between the cell and the antenna for a heating time of 10 ms and a dipole moment of (a) 1 mA · m and (b) 6 mA · m.

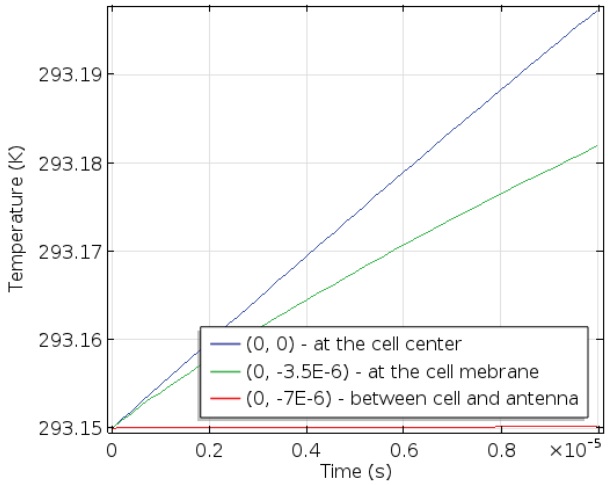

Fig. 7. The temperature variation as a function of time experienced at the cell center, at the cell membrane and between the cell and the antenna for a heating time of 10 μs.

At this point, it is relevant to note that due to the size and energy constraints of simple nanosensors, it is technologically very challenging for a nano-device to generate a high power carrier frequency in the THz band. As a result, classical communication paradigms based on the transmission of continuous signals might not be used in EM intra-body communications. Alternatively, very short pulses can be generated and radiated from the nanoscale [36]. In line with the capabilities of nano-transceivers, the heating time has been reduced to 10 μs to mimic the transmission of short pulses.

It can be noticed from Fig. 7 that even though the cell follows the same heating analogy presented above, the temperature change is insignificant when the exposure time is reduced to 10 μs. The presented conclusion is fundamental as it proofs that short pulses can be utilized in intra-body communication without having any severe effect on the body cells. Hence, carrier-less pulse based modulation schemes are considered significant candidates for intra-body communication at the nanoscale.

V. Conclusion

This paper developed a novel thermal noise model for intra-body communication based on the diffusive heat flow theory.

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In particular, it presented a mathematical framework which models the molecular absorption phenomenon experienced by biological cells. The analysis of such phenomenon is fundamental as absorption not only compromises the propagation of EM signals in the body, but it can also result in photothermal damage to the biological entities in the system. Upon the EM radiation of nano-antennas, cells in the human body will subsequently release the energy captured from EM fields as heat to their immediate surroundings, resulting in a temperature increase. The quantization of the temperature allows further the calculation of the molecular absorption noise. Both single as well as multiple particle analysis have been conducted to compute discrepancies in temperature at both the THz band as well as optical window. In addition, EM simulations have been carried out via COMSOL Multiphysics to complete the analytical framework by analyzing the effect of altering the power of the EM source as well as changing the heating exposure time on the temperature rise. It has been concluded that based on the intensities and capabilities of the available nano-antennas, which permits short-pulse transmission, the increase in temperature experienced in the medium is minimal. This conclusion indicates that the THz band and the optical window can be utilized in intra-body communication without having any severe effect on the body cells. Specifically, the short-pulse nature of the propagating wave sheds the light on the future modulation schemes that ought to be used in intra-body communication. Another advantage perceived from the presented model lies in the ability to control the power of the EM source or the pulse duration. Increasing the power to certain levels allows temperature elevation suited for biomedical applications such as cancer treatment.

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