Available online at www.sciencedirect.com
ScienceDirect
Sensors and Actuators B 127 (2007) 54–62
SENSORS AND ACTUATORS B CHEMICAL
www.elsevier.com/locate/snb

Wireless Joule nanoheaters

Christian Falconi [a,b,*], Arnaldo D'Amico [a,b], Zhong Lin Wang [c]

[a] *Department of Electronic Engineering, University of Tor Vergata, Via del Politecnico 1, 00133 Rome, Italy*
[b] *CNR IDAC, Via Fosso del Cavaliere 100, 00133 Rome, Italy*
[c] *School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0245, USA*

Available online 5 July 2007

Abstract

In principle, biocompatible, wireless nanotransducers might be useful for many *in vivo* biomedical applications such as hyperthermia, thermal ablation, targeted drug delivery, and *in vivo* monitoring of physiological parameters. In this article, we theoretically study the possibility of applying ring-shaped wireless Joule nanoheaters as possible nanovectors for targeted drug delivery, hyperthermia, and thermal ablation. This examination may offer an approach for guiding practical experiments.

Keywords: Wireless nanotransducers; Wireless Joule nanoheaters; Targeted drug delivery; Nanorings; Zinc oxide nanostructures

1. Introduction

Nanotechnology opens the way to a new generation of nano-sized transducers for *in vivo* biomedical applications, such as targeted drug delivery, hyperthermia, thermal ablation, and *in vivo* monitoring of physiological parameters. In most cases transducers are physically connected to electronic circuits by wires; this, however, may not be the best strategy for biomedical applications which require very small devices. We recently observed that, in these cases, a wireless approach might be more convenient and should be systematically explored [1]; in fact, only a few wireless nanoactuators have been proposed. In particular, wireless nanoheaters can selectively damage target cells by heating (hyperthermia, or thermal ablation if the temperature is so high that cells are destroyed); based on this principle, magnetic nanoparticles [2–4] and gold nanoshells [5] have been used for killing cancer cells by thermal ablation. The potential of both magnetic nanoparticles (transducing the magnetic field into position) [4,6,7] and of gold nanoshells [8,9] for targeted drug delivery has also been investigated. Furthermore, there might be many other opportunities for wireless nanotransducers [1].

As to hyperthermia or thermal ablation, other wireless nanoheaters might be used; as to drug delivery, nanotransducers and therapeutics may be included in a special coating which should be broken-perforated-dissolved-melt upon excitation, thus releasing drugs in a selective, controlled, and accurate manner [1] (this is a generalization of the "photothermally induced" targeted drug delivery reported in [8,9]). In all cases, the selectivity (i.e. the ability to selectively deliver drugs or to heat only the target cells) may be obtained by focusing the exciting waves only in specific regions of the body and/or by properly functionalizing the coating so that it will preferentially bind to specific cells (for instance, attaching antibodies which only bind to specific molecules present on the surface of cancer cells). As an example, in this paper we study ring-shaped nanostructures which can be wirelessly excited by means of an electromagnetic field (wireless Joule nanoheater); as other wireless nanoheaters, these nanostructures could be useful for hyperthermia, thermal ablation, or targeted drug delivery. As a second example, an electromagnetic field may induce mechanical vibrations in piezoelectric nanostructures (nanopumps, nanoscissors, vibration nanoheaters, etc.) which could be useful in medical applications [1].

Wireless nanotransducers could also be used for *in vivo* monitoring of physiological parameters [1]. As an example, if we again consider an electromagnetically excited ring-shaped nanostructure, after the excitation is removed, the current in the ring will decay and re-irradiate an electromagnetic wave, eventually with characteristics related to a measurand [1]. In the same manner, if we again consider an electromagnetically excited piezoelectric nanostructure, after the excitation is removed, the mechanical vibrations will decay, re-irradiating an electromagnetic wave, eventually with characteristics related to a measurand [1] (viscosity, flow, etc.). Obviously, in the case of

* Corresponding author at: Department of Electronic Engineering, University of Tor Vergata, Via del Politecnico 1, 00133 Rome, Italy.
E-mail address: falconi@eln.uniroma2.it (C. Falconi).

0925-4005/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.snb.2007.07.002

these "wireless nanosensors", obtaining a reasonable accuracy would require an accurate detection of the re-irradiated electromagnetic fields (we mention that the waves re-irradiated by different nanostructures, even with a random orientation, would still add along the direction of the linearly polarized exciting electromagnetic radiation); although different wireless sensors (e.g. see [10]) are being considered for other applications, the proposed wireless *nano*sensors might be best suited for *in vivo* monitoring of physiological parameters.

Beside wireless nanotransducers, different methods for applying nanotechnology to medicine are also being explored [11–17]; as an example, nanocells with a diameter smaller than 200 nm have been used as drug delivery systems in a successful attempt for combining traditional chemotherapy with anti-angiogenesis [17]. In general, a fundamental concern is the patient safety even after long-term exposure to the therapeutic nanoparticles (especially with reference to toxicity and to the risk of undesired aggregation and obstruction of blood vessels).

Recently, nanostructures which seem ideally suited for fabricating wireless nanotransducers for biomedical applications have been reported [18–21]: almost defect-free, self-assembled monocrystals of zinc oxide (ZnO). In fact, as to signal conversion, the geometries of these nanostructures (rings [19], helixes [20], etc.) permit an efficient electromagnetic wireless interaction; moreover, zinc oxide is piezoelectric. Additionally, these single-crystal nanostructures have excellent mechanical properties. Other advantages concerning the patient safety are also likely: zinc oxide is biocompatible and biosafe (i.e. non-toxic); besides, the unique geometries of zinc oxide nanostructures should, hopefully, prevent the obstruction of blood vessels; finally, once immersed in water, zinc oxide nanostructures are automatically dissolved after a few hours. As a possible application of the unique properties of these self-assembled ZnO nanostructures, wirelessly excited ZnO nanohelixes could selectively damage the target cells [1] (by heating or by inertial cavitation [22]) and could be automatically dissolved into the body after use (these are ideal characteristics for *in vivo* biomedical applications as zinc oxide is not toxic and there would be no self-aggregation risks).

In this paper we focus on wireless Joule nanoheaters. Since the electromagnetic-to-heat transduction process does not rely on the optical properties of the nanostructures, the addition of non-transparent coating layers does not necessarily degrade the signal conversion efficiency. In Section 2 we discuss some simplifying assumptions which will be used throughout this paper and we discuss an electrical model for wireless Joule heaters; this model is employed in Section 3 in order, first, to maximize the temperature difference between the nanoheater and the surroundings and, second, to estimate the extinction cross-section. Since heat transfer at nanoscale is extremely complex [23–29] an accurate, quantitative evaluation of the thermal resistance between a nanoring and the surroundings is, practically, impossible; however, in Section 4 we discuss a qualitative analysis which provides insight for the design of effective wireless Joule heaters. In Section 5 we discuss the potential use of wireless Joule nanoheaters for *in vivo* biomedical applications; although various techniques can be used for fabricating nanorings [31–33], in Section 6, as an example, we apply our analysis to the design of multi-shell (two layers) wireless Joule nanoheaters based on zinc oxide nanorings [19,21]. Preliminary conclusions are drawn in Section 7.

2. Electrical model for wireless Joule heaters

According to Faraday's law, alternating electromagnetic fields generate alternating electrical currents inside loop-shaped structures, as schematically shown in Fig. 1. Electrical currents produce heat due to the Joule effect (wireless Joule heaters); this wideband transduction mechanism does not require an exciting radiation with a high spectral purity. Although we are mainly interested in *nano*sized heaters, in this section we discuss an electrical model for toroidal wireless Joule heaters.

2.1. Toroidal geometry

We consider a simplified toroidal geometry characterized by r_0, radius of the tube, and R, radius of the torus (see Fig. 1 for a section of the toroidal ring). This choice allows to find very simple analytical relations and to focus on the very important role of the dimensionless aspect ratio ζ (see, for instance, the conclusions), which is defined as follows

$$\zeta = \frac{R}{r_0}. \tag{1}$$

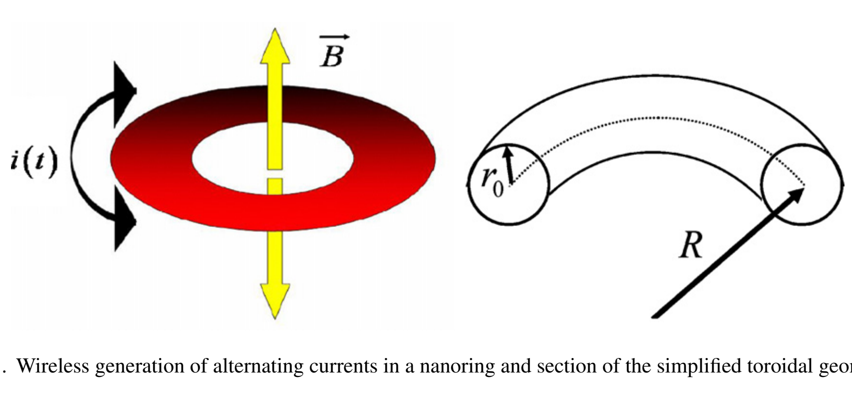

Fig. 1. Wireless generation of alternating currents in a nanoring and section of the simplified toroidal geometry.