International Journal of Enhanced Research in Science Technology & Engineering, ISSN: 2319-7463
Vol. 3 Issue 4, April-2014, pp: (447-450), Impact Factor: 1.252, Available online at: www.erpublications.com

Effective Wireless Non Radiative Mid Range Energy Transfer

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Abstract: **We investigate whether, and to what extent, the physical phenomenon of long-lifetime resonant electromagnetic states with localized slowly-evanescent field patterns can be used to transfer energy efficiently over non-negligible distances, even in the presence of extraneous environmental objects. Via detailed theoretical and numerical analyses of typical real-world model-situations and realistic material parameters, we establish that such a non-radiative scheme can lead to "strong coupling" between two medium-range distant such states and thus could indeed be practical for efficient medium-range wireless energy transfer.**

I. Introduction

In the early days of electromagnetism, before the electrical-wire grid was deployed, serious interest and effort was devoted (most notably by Nikola Tesla [1]) towards the development of schemes to transport energy over long distances without any carrier medium (e.g. wirelessly). These efforts appear to have met with little success. Radiative modes of omni-directional antennas (which work very well for information transfer) are not suitable for such energy transfer, because a vast majority of energy is wasted into free space. Directed radiation modes, using lasers or highly-directional antennas, can be efficiently used for energy transfer, even for long distances (transfer distance $L_{TRANS} \gg L_{DEV}$, where L_{DEV} is the characteristic size of the device), but require existence of an uninterruptible line-of-sight and a complicated tracking system in the case of mobile objects. Rapid development of autonomous electronics of recent years (e.g. laptops, cell- phones, house-hold robots, that all typically rely on chemical energy storage) justifies revisiting investigation of this issue. Today, we face a different challenge than Tesla: since the existing electrical-wire grid carries energy almost everywhere, even a medium-range ($L_{TRANS} \approx few*L_{DEV}$) wireless energy transfer would be quite usefulfor many applications. which rely on non-radiative modes (magnetic induction), but they are restricted to very close-range ($L_{TRANS} \ll L_{DEV}$) or very low-power (~mW) energy transfers [2,3,4,5,6]. In contrast to all the above schemes, we investigate the feasibility of using long-lived oscillatory resonant electromagnetic modes, with localized slowly-evanescent field patterns, for efficient wireless non-radiative mid-range energy transfer. The proposed method is based on the well-known principle of resonant coupling (the fact that two same-frequency resonant objects tend to couple, while interacting weakly with other off-resonant environmental objects) and, in particular, resonant evanescent coupling (where the coupling mechanism is mediated through the overlap of the non-radiative near-fields of the two objects). This well-known physics leads trivially to the result that energy can be efficiently coupled between objects in the extremely near field (e.g. in optical waveguide or cavity couplers and in resonant inductive electric transformers).
However, it is far from obvious how this same physics performs at mid-range distances and, to our knowledge, there is no work in the literature that demonstrates efficient energy transfer for distances a few times larger that the largest dimension of both objects involved in the transfer. In the present paper, our detailed theoretical and numerical analysis shows that such an efficient mid-range wireless energy-exchange can actually be achieved, while suffering only modest transfer and dissipation of energy into other off-resonant objects, provided the exchange system is carefully designed to operate in a regime of "strong coupling" compared to all intrinsic loss rates. The physics of "strong coupling" is also known but in very different areas, such as those of light-matter interactions [7]. In this favourable operating regime, we quantitatively address the following questions: up to which distances can such a scheme be efficient and how sensitive is it to external perturbations? The omnidirectional but stationary (non-lossy) nature of the near field makes this mechanism suitable for mobile wireless receivers. It could therefore have a variety of possible applications including for example, placing a source (connected to the wired electricity network) on the ceiling of a factory room, while devices (robots, vehicles, computers, or similar) are roaming freely within the room. Other possible applications include electric-engine buses, RFIDs, and perhaps even nano-robots.

II. Range and rate of coupling

The range and rate of the proposed wireless energy-transfer scheme are the first subjects of examination, without considering yet energy drainage from the system for use into work. An appropriate analytical framework for modeling this resonant energy-exchange is that of the well-known coupled-mode theory (CMT) [8]. In this picture, the field of the system of two resonant objects 1 and 2 is approximated by $F(r,t) \approx a_1(t)F_1(r)+a_2(t)F_2(r)$, where $F_{1,2}(r)$ are the eigenmodes of 1 and 2 alone, and then the field amplitudes $a_1(t)$ and $a_2(t)$ can be shown [8] to satisfy, to lowest order:

Da1/dt=-i(ω1- iT1) a1 + ika2
Da1/dt=-i(ω2-iT2)a2

where $\omega_{1,2}$ are the individual eigen frequencies, $\Gamma_{1,2}$ are the resonance widths due to the objects' intrinsic (absorption, radiation etc.) losses, and κ is the coupling coefficient. Eqs.(1) show that at exact resonance ($\omega_1=\omega_2$ and $\Gamma_1=\Gamma_2$), the normal modes of the combined system are split by ; the energy exchange between the two objects takes place in time and is nearly perfect, apart for losses, which are minimal when the coupling rate is much faster than all loss rates (k>>T1,2) [9]. It is exactly this ratio k/(T1T2)^1/2 that we will set as our figure-of-merit for any system under consideration for wireless energy-transfer, along with the distance over which this ratio can be achieved. The desired optimal regime k/(T1T2)^1/2>>1 is called "strong-coupling" regime.

Consequently, our energy-transfer application requires resonant modes of high Q=ω/2Γ for low (slow) intrinsic-loss rates Γ, and this is why we propose a scheme where the coupling is implemented using, not the lossy radiative far-field, but the evanescent (non-lossy) stationary near-field. Furthermore, strong (fast) coupling rate κ is required over distances larger than the characteristic sizes of the objects, and therefore, since the extent of the near-field into the air surrounding a finite-sized resonant object is set typically by the wavelength (and quantified rigorously by the "radiation caustic"), this mid-range non-radiative coupling can only be achieved using resonant objects of subwavelength size, and thus significantly longer evanescent field-tails. This is a regime of operation that has not been studied extensively, since one usually prefers short tails to minimize interference with nearby devices. As will be seen in examples later on, such subwavelength resonances can often be accompanied with a high radiation-Q, so this will typically be the appropriate choice for the possibly-mobile resonant device-object d. Note, though, that the resonant source-object s will in practice often be immobile and with less stringent restrictions on its allowed geometry and size, which can be therefore chosen large enough that the near-field extent is not limited by the wavelength (using for example waveguides with guided modes tuned close to the "light line" in air for slow exponential decay therein).

The proposed scheme is very general and any type of resonant structure (e.g. electromagnetic, acoustic, nuclear) satisfying the above requirements can be used for its implementation. As examples and for definiteness, we choose to work with two well-known, but quite different, electromagnetic resonant systems: dielectric disks and capacitively-loaded conducting-wire loops. Even without optimization, and despite their simplicity, both will be shown to exhibit acceptably good performance.

Capacitively-loaded conducting-wire loops

Consider a loop of radius r of conducting wire with circular cross-section of radius a connected to a pair of conducting parallel plates of area A spaced by distance d via a dielectric of relative permittivity ε and everything surrounded by air . The wire has inductance L, the plates have capacitance C and then the system has a resonant mode, where the nature of the resonance lies in the periodic exchange of energy from the electric field inside the capacitor, due to the voltage across it, to the magnetic field in free space, due to the current in the wire. Losses in this resonant system consist of ohmic loss absR inside the wire and radiative loss radR into free space. Mode-solving calculations for this type of RLC-circuit resonances were performed using again two independent methods: numerically, 3D finite-element frequency-domain (FEFD) simulations (which solve Maxwell's Equations in frequency domain exactly apart for spatial discretization) were conducted [11], in which the boundaries of the conductor were modeled using a complex impedance η=(μw/2σ)^1/2 boundary condition, valid as long as ηc?η0<<1 [12] ($<10^{-5}$ for copper in the microwave), where μo, εo and ηo= (μo/εo) are the magnetic permeability, electric permittivity and impedance of free space and σ is the conductivity of the d A conductor; analytically, the formulas L=μor[ln(8r/a)-2] [13] and C=εoεA/d , and, in the desired subwavelength-loop (r«λ) limit, the quasi-static formulas Rabs = ηc r/a· (which takes skin-depth effects into account) and Rrad ≈ 3.14 / 6.ηo (r/lamda)^4· [13] were used to determine the resonant frequency ω=1/(LC)^1/2 and its quality factors and . By tuning the capacitance and thus the resonant frequency, the total Q becomes highest for some optimal frequency determined by the loop parameters: at low frequencies it is dominated by ohmic loss and at high frequencies by radiation. The two methods are again in very good agreement and show that expected quality factors in the microwave are Qabs≥1000 and Qrad ≥ 10000.
For the rate of energy transfer between two loops 1 and 2 at distance D between their centers : numerically, the FEFD mode-solver simulations give κ again through the frequency splitting (=2k) of the normal modes of the combined system; analytically, κ is given by k=ωM/2(L1L2)^1/2, where M is the mutual inductance of the two loops, which, in the quasi-static limit r«D«λ and for the relative orientation is M=3.14/2.μo(r1r2)^2/D^3 [12], which means that ω/2k=(D/(r1r2)^1/2)^3. Then, and for medium distances D/r= 10-3, the two methods agree well, and we finally find coupling-to-loss ratios, which peak at a frequency between those where the single-loop $Q_{1,2}$ peak and are in the range k/T

= 0.5-50. It is important to appreciate the difference between such a resonant-coupling inductive scheme and the well-known non-resonant inductive scheme for energy transfer. Using CMT it is easy to show that, keeping the geometry and the energy stored at the source fixed, the resonant inductive mechanism allows for $\sim Q^2$ ($\sim 10^6$) times more power delivered for work at the device than the traditional non-resonant mechanism. This is why only close-range contact-less medium-power (~W) transfer is possible with the latter [2,3], while with resonance either close-range but large-power (~kW) transfer is allowed [4,5] or, as currently proposed, if one also ensures operation in the strongly-coupled regime, medium-range and medium-power transfer is possible. Capacitively-loaded conductive loops are actually being widely used also as resonant antennas (for example in cell phones), but those operate in the far-field regime with D/r»1, r/λ~1, and the radiation Q's are intentionally designed to be small to make the antenna efficient, so they are not appropriate for energy transfer.

III. Influence of extraneous objects

Clearly, the success of the proposed resonance-based wireless energy-transfer scheme depends strongly on the robustness of the objects' resonances. Therefore, their sensitivity to the near presence of random non-resonant extraneous objects is another aspect of the proposed scheme that requires analysis. The appropriate analytical model now is that of perturbation theory (PT) [8], which suggests that in the presence of an extraneous object e the field amplitude $a_1(t)$ inside the resonant object 1 satisfies, to first order:

Da1/dt=-i(w1-iT1)a1+i(k11-e=iT1-e)a1

where again ω_1 is the frequency and the intrinsic (absorption, radiation etc.) loss rate, while is the frequency shift induced onto 1 due to the presence of e and is the extrinsic due to e (absorption inside e, scattering from e etc.) loss rate [14]. The frequency shift is a problem that can be "fixed" rather easily by applying to every device a feedback mechanism that corrects its frequency (e.g. through small changes in geometry) and matches it to that of the source. However, the extrinsic loss can be detrimental to the functionality of the energy-transfer scheme, because it cannot be remedied, so the total loss rate and the corresponding figure-of-merit k(e)/(T1et2e)^1/2, where κ the perturbed coupling rate, must be quantified.

Capacitively-loaded conducting wire

The conducting-wire loops, the influence of extraneous objects on the resonances is nearly absent. The reason is that, in the quasi-static regime of operation (r«λ) that we are considering, the near field in the air region surrounding the loop is predominantly magnetic (since the electric field is localized inside the capacitor), therefore extraneous non-metallic objects e that could interact with this field and act as a perturbation to the resonance are those having significant magnetic properties (magnetic permeability Re{μ}>1 or magnetic loss Im{μ}>0). Since almost all every-day materials are non-magnetic, they respond to magnetic fields in the same way as free space, and thus will not disturb the resonance of a conducting-wire loop. To get only a rough estimate of this disturbance, we use the PT formulawith the numerical results for the field of a rectangular object of dimensions 30cm x 30cm x 1.5m and permittivity ε=49+16i (human muscles) residing between the loops and almost standing on top of one capacitor (~3cm away from it) and find and for ~10cm away . Thus, for ordinary distances (~1m) and placements (not immediately on top of the capacitor) or for most ordinary extraneous objects e of much smaller loss-tangent, we conclude that it is indeed fair to say that and that K1e/T(e) =k/T=0.5-50. The only perturbation that is expected to affect these resonances is a close proximity of large metallic structures.

An extremely important implication of this fact relates to safety considerations for human beings. Humans are also non-magnetic and can sustain strong magnetic fields without undergoing any risk. A typical example, where magnetic fields B~1T are safely used on humans, is the Magnetic Resonance Imaging (MRI) technique for medical testing. In contrast, the magnetic near-field required by our scheme in order to provide a few Watts of power to devices is only $B \sim 10^{-4}$ T, which is actually comparable to the magnitude of the Earth's magnetic field. Since, as explained above, a strong electric near-field is also not present and the radiation produced from this non-radiative scheme is minimal, it is reasonable to expect that our proposed energy-transfer method should be safe for living organisms. In comparison of the two classes of resonant systems under examination, the strong immunity to extraneous objects and the absence of risks for humans probably makes the conducting-wire loops the preferred choice for many real-world applications; on the other hand, systems of disks (or spheres) of high (effective) refractive index have the advantage that they are also applicable to much smaller length-scales (for example in the optical regime dielectrics prevail, since conductive materials are highly lossy).

Acknowledgment

I gratefully acknowledge the contributions of Prof. Sukhwinder Singh, for his work and contribution to this document.

Conclusion

In conclusion, we present a scheme based on "strongly-coupled" resonances for mid-range wireless non-radiative energy transfer. Although our consideration has been for a static geometry (namely κ and Γ_e were independent of time), all the results can be applied directly for the dynamic geometries of mobile objects, since the energy-transfer time (1κ−μ−~1100s for microwave applications) is much shorter than any timescale associated with motions of macroscopic objects. Analyses of very simple implementation geometries provide encouraging performance characteristics and further improvement is expected with serious design optimization. Thus the proposed mechanism is promising for many modern applications. For example, in the macroscopic world, this scheme could potentially be used to deliver power to robots and/or computers in a factory room, or electric buses on a highway (source-cavity would in this case be a "pipe" running above the highway). In the microscopic world, where much smaller wavelengths would be used and smaller powers are needed, one could use it to implement optical inter-connects for CMOS electronics, or to transfer energy to autonomous nano-objects (e.g. MEMS or nano-robots) without worrying much about the relative alignment between the sources and the devices.

As a venue of future scientific research, enhanced performance should be pursued for electromagnetic systems either by exploring different materials, such as plasmonic or metallo-dielectric structures of large effective refractive index, or byfine-tuning the system design, for example by exploiting the earlier mentioned interference effects between the radiation fields of the coupled objects. Furthermore, the range of applicability could be extended to acoustic systems, where the source and device are connected via a common condensed-matter object.

References

[1]. Tesla, N. "Apparatus for transmitting electrical energy." U.S. patent number 1,119,732, issued in December 1914.
[2]. Fernandez, J. M. and Borras, J. A. "Contactless battery charger with wireless control link." U.S. patent number 6,184,651, issued in February 2001.
[3]. Ka-Lai, L., Hay, J. W. and Beart, P. G. W. "Contact-less power transfer." U.S. patent number 7,042,196, issued in May 2006. (SplashPower Ltd., www.splashpower.com)
[4]. Esser, A. and Skudelny, H.-C. "A new approach to power supplies for robots." IEEE Trans. on industry applications **27**, 872 (1991).
[5]. Hirai, J., Kim, T.-W. and Kawamura, A. "Wireless transmission of power and information and information for cableless linear motor drive." IEEE Trans. on power electronics **15**, 21 (2000).
[6]. Scheible, G., Smailus, B., Klaus, M., Garrels, K. and Heinemann, L. "System for wirelessly supplying a large number of actuators of a machine with electrical power." U.S. patent number 6,597,076, issued in July 2003. (ABB, www.abb.com)
[7]. Takao, A. et al. "Observation of strong coupling between one atom and a monolithic microresonator.", Nature **443**, 671 (2006).
[8]. Haus, H. A. Waves and Fields in Optoelectronics (Prentice-Hall, New Jersey, 1984).
[9]. The CMT model is valid exactly for this optimal operational regime of well-defined resonances. Its range of applicability does not include very-close-distance coupling, since there the necessary condition $\kappa \ll \omega_{1,2}$ does not hold, neither large-distance far-field coupling, since it fails to predict far-field interference effects and accurate radiation patterns; rather CMT is exactly suitable for the medium-distance near-field coupling of our interest. Thus the use of this model is justified and the parameters κ, $\Gamma_{1,2}$ are well defined.
[10]. Note that for the 3D case the computational complexity would be immensely increased, while the physics would not be significantly different. For example, a spherical object of ε=147.7 has a whispering gallery mode with m=2, Qrad=13962, and λ/r=17.
[11]. COMSOL Inc. (www.comsol.com)
[12]. Jackson, J. D. Classical Electrodynamics (Wiley, New York, 1999).
[13]. Balanis, C. A. Antenna Theory: Analysis and Design (Wiley, New Jersey, 2005).
[14]. The first-order PT model is valid only for small perturbations. Nevertheless, the parameters , K11-e, T1-e are well defined, even outside that regime, if a is taken to be the amplitude of the exact perturbed mode.