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(54) **WIRELESS ENERGY TRANSFER WITH HIGH-Q TO MORE THAN ONE DEVICE**

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(58) **Field of Classification Search**

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See application file for complete search history.

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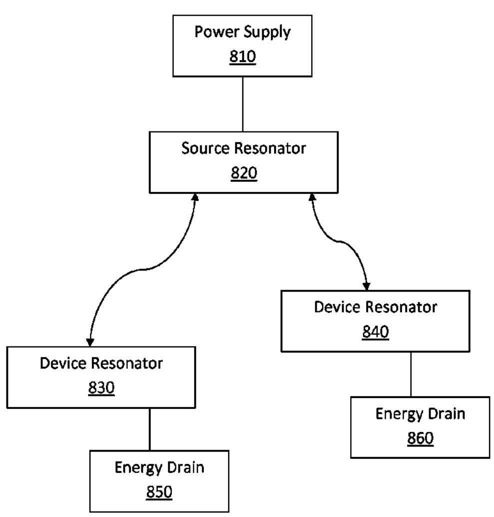
(57) **ABSTRACT**

Described herein are embodiments of a source high-Q resonator, optionally coupled to an energy source, a second high-Q resonator, optionally coupled to an energy drain that may be located a distance from the source resonator. A third high-Q resonator, optionally coupled to an energy drain that may be located a distance from the source resonator. The source resonator and at least one of the second resonator and third resonator may be coupled to transfer electromagnetic energy from said source resonator to said at least one of the second resonator and third resonator.

44 Claims, 8 Drawing Sheets



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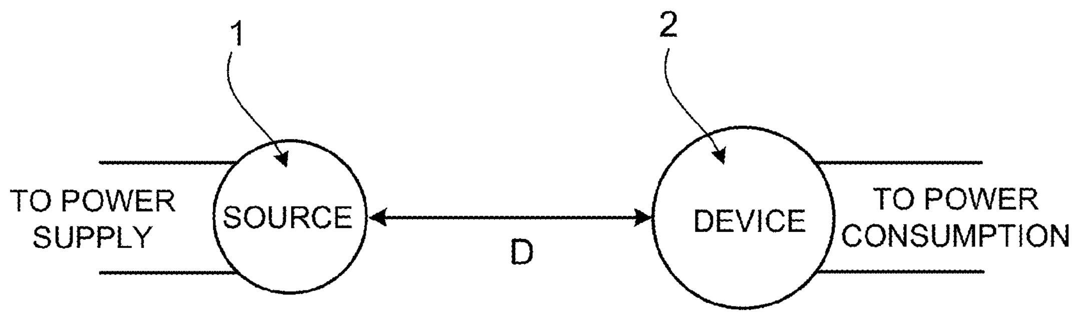

FIG. 1

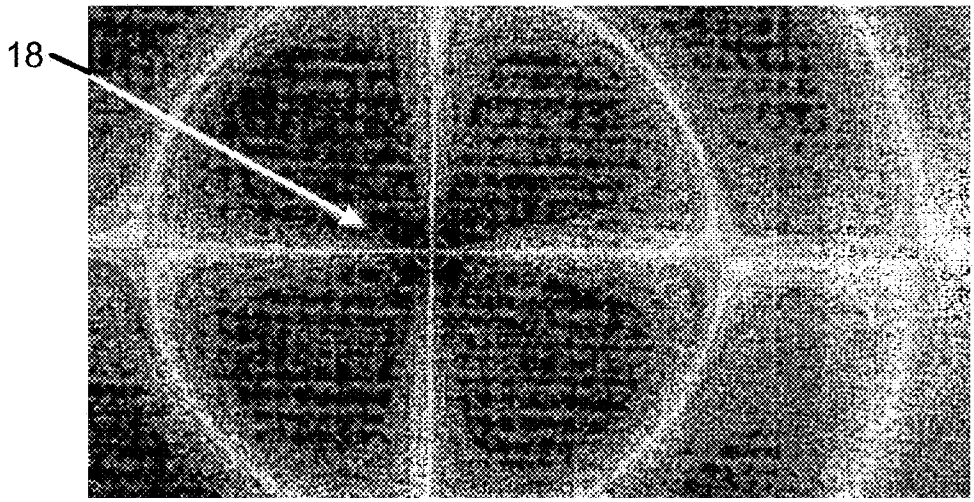

FIG. 2A

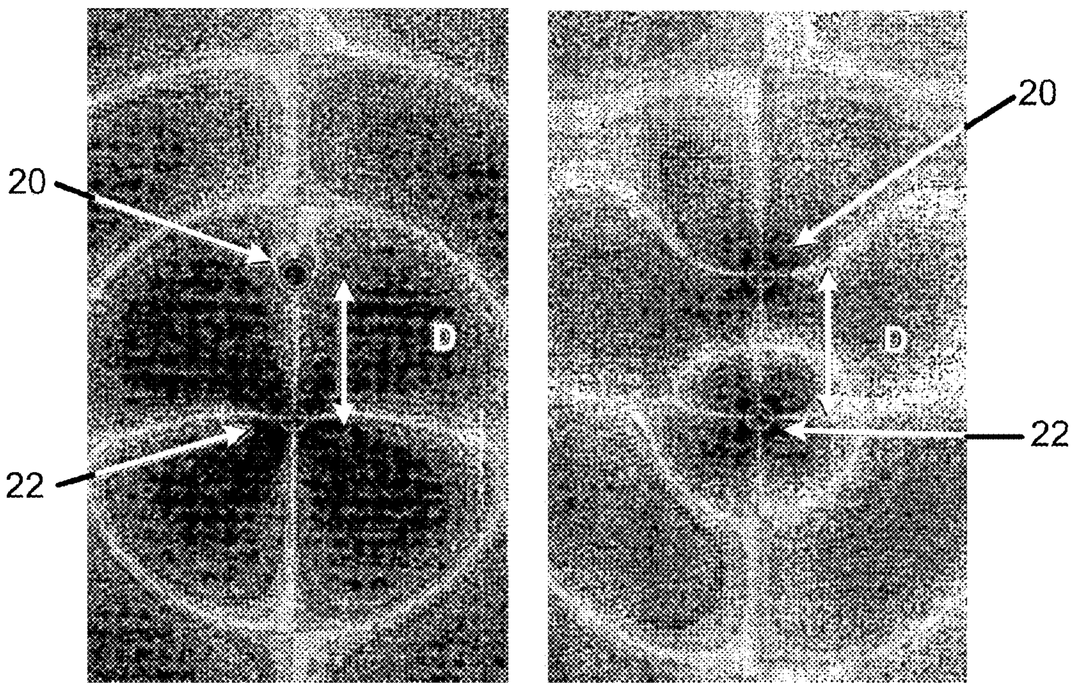

FIG. 2B

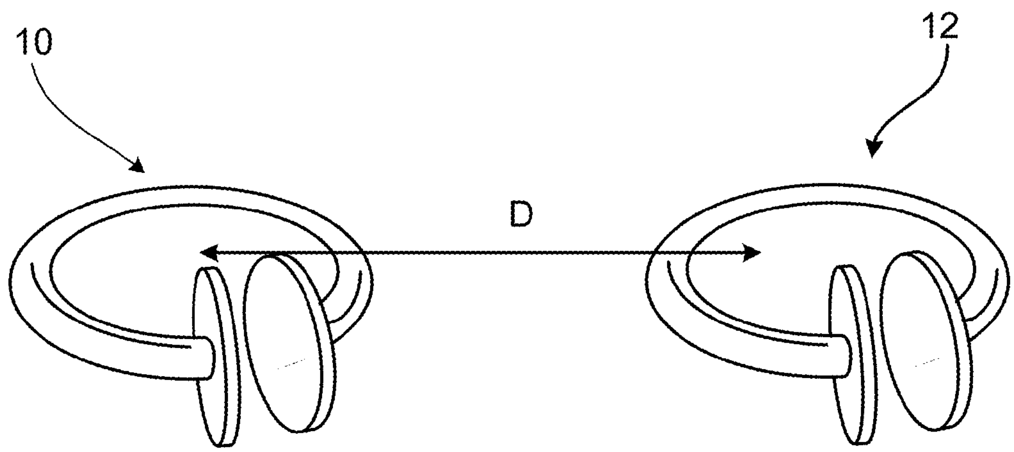

FIG. 3

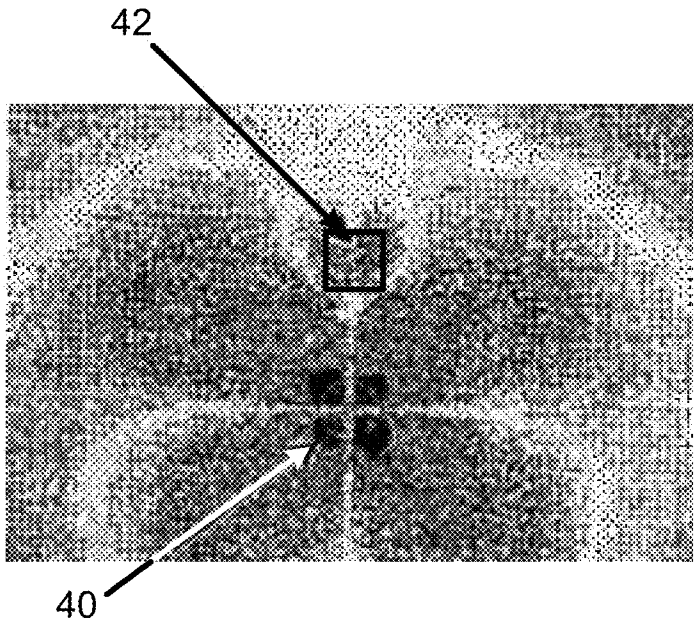

FIG. 4A

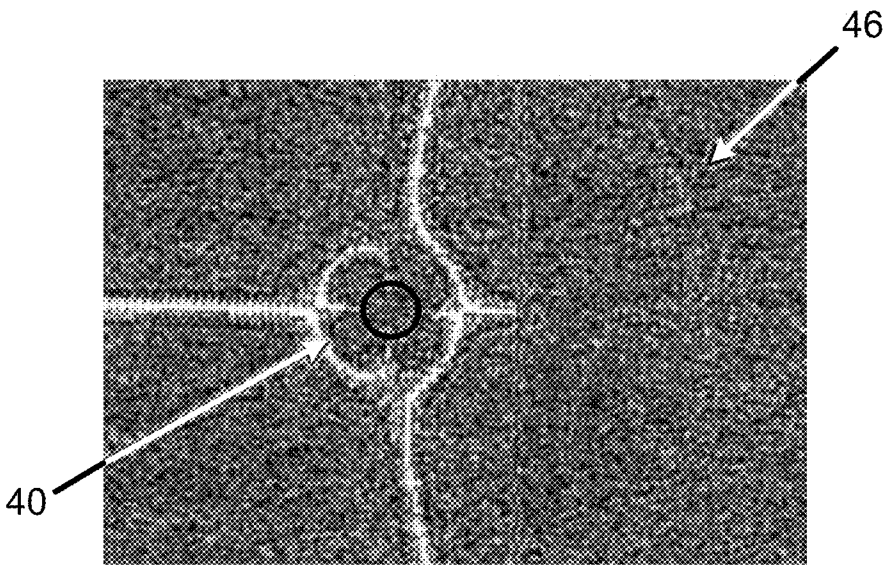

FIG. 4B

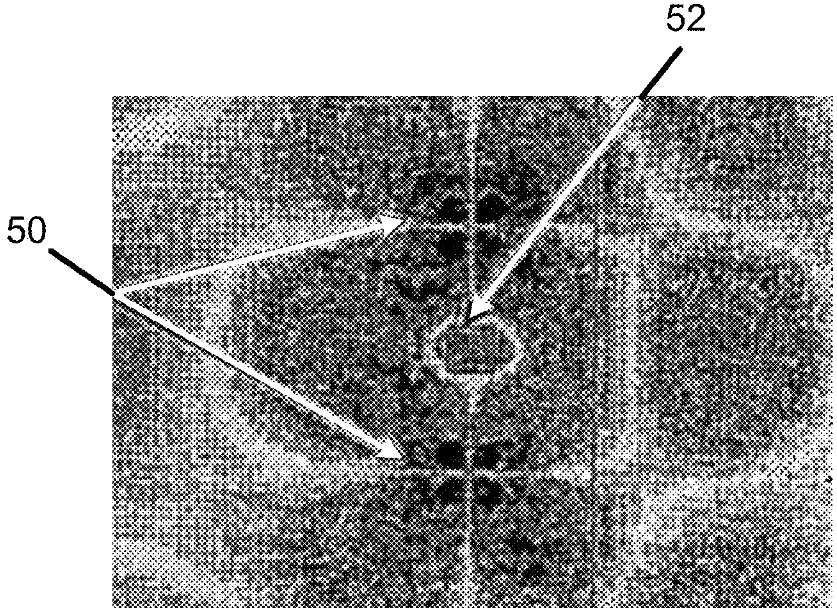

FIG. 5

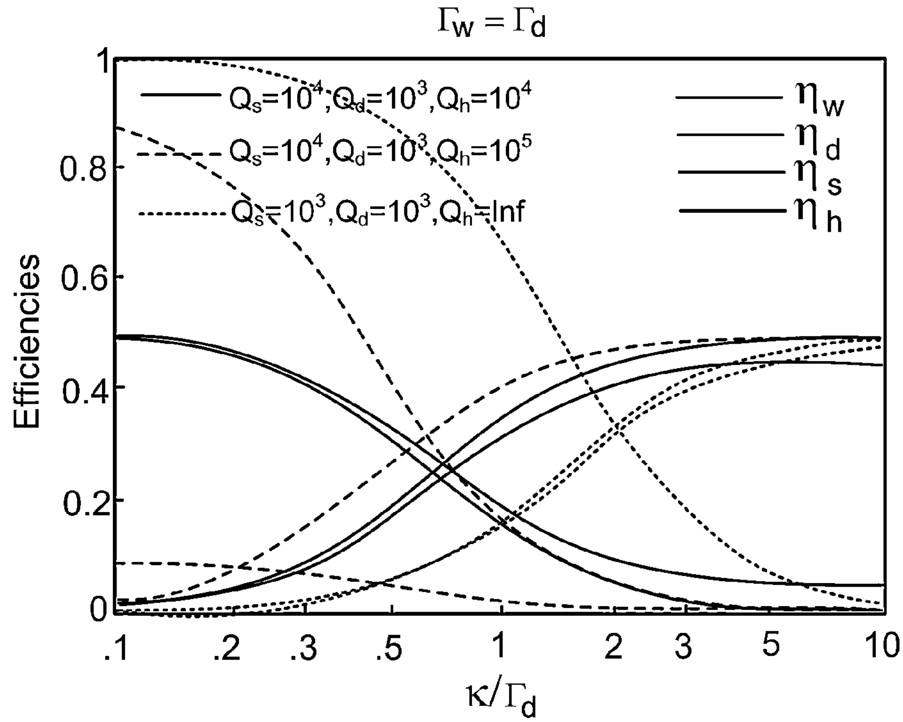
$\Gamma_w = \Gamma_d$
$Q_s=10^4, Q_d=10^3, Q_h=10^4$
$Q_s=10^4, Q_d=10^3, Q_h=10^5$
$Q_s=10^3, Q_d=10^3, Q_h=Inf$
η_w
η_d
η_s
η_h
Efficiencies
κ/Γ_d
0
0.2
0.4
0.6
0.8
1
.1
.2
.3
.5
1
2
3
5
10

FIG. 6A

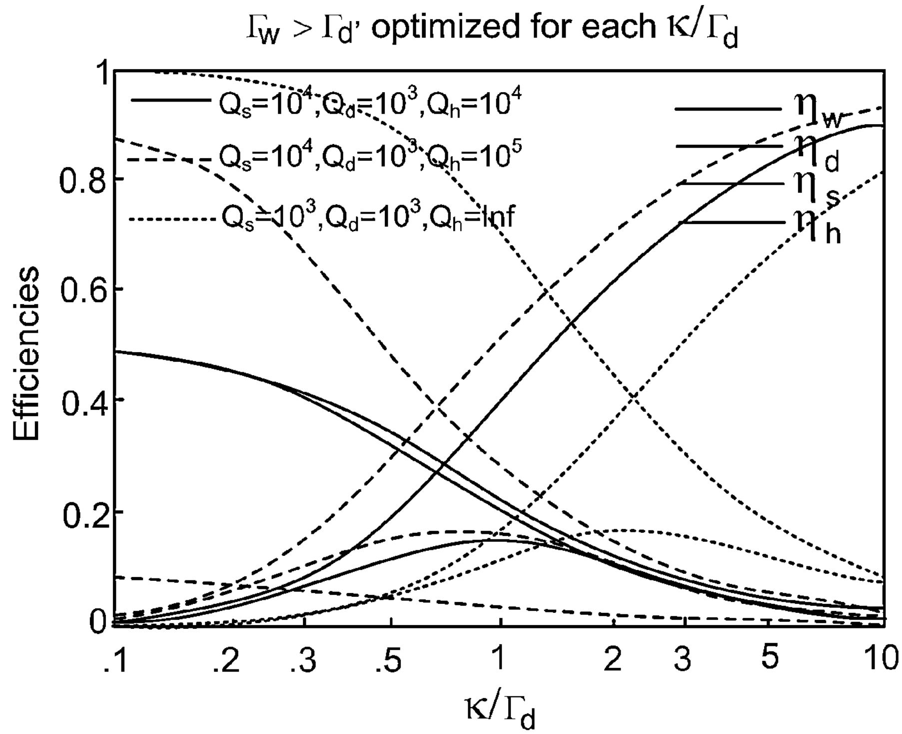
$\Gamma_w > \Gamma_d$, optimized for each κ/Γ_d
$Q_s=10^4, Q_d=10^3, Q_h=10^4$
$Q_s=10^4, Q_d=10^3, Q_h=10^5$
$Q_s=10^3, Q_d=10^3, Q_h=Inf$
η_w
η_d
η_s
η_h
Efficiencies
κ/Γ_d
0
0.2
0.4
0.6
0.8
1
.1
.2
.3
.5
1
2
3
5
10

FIG. 6B

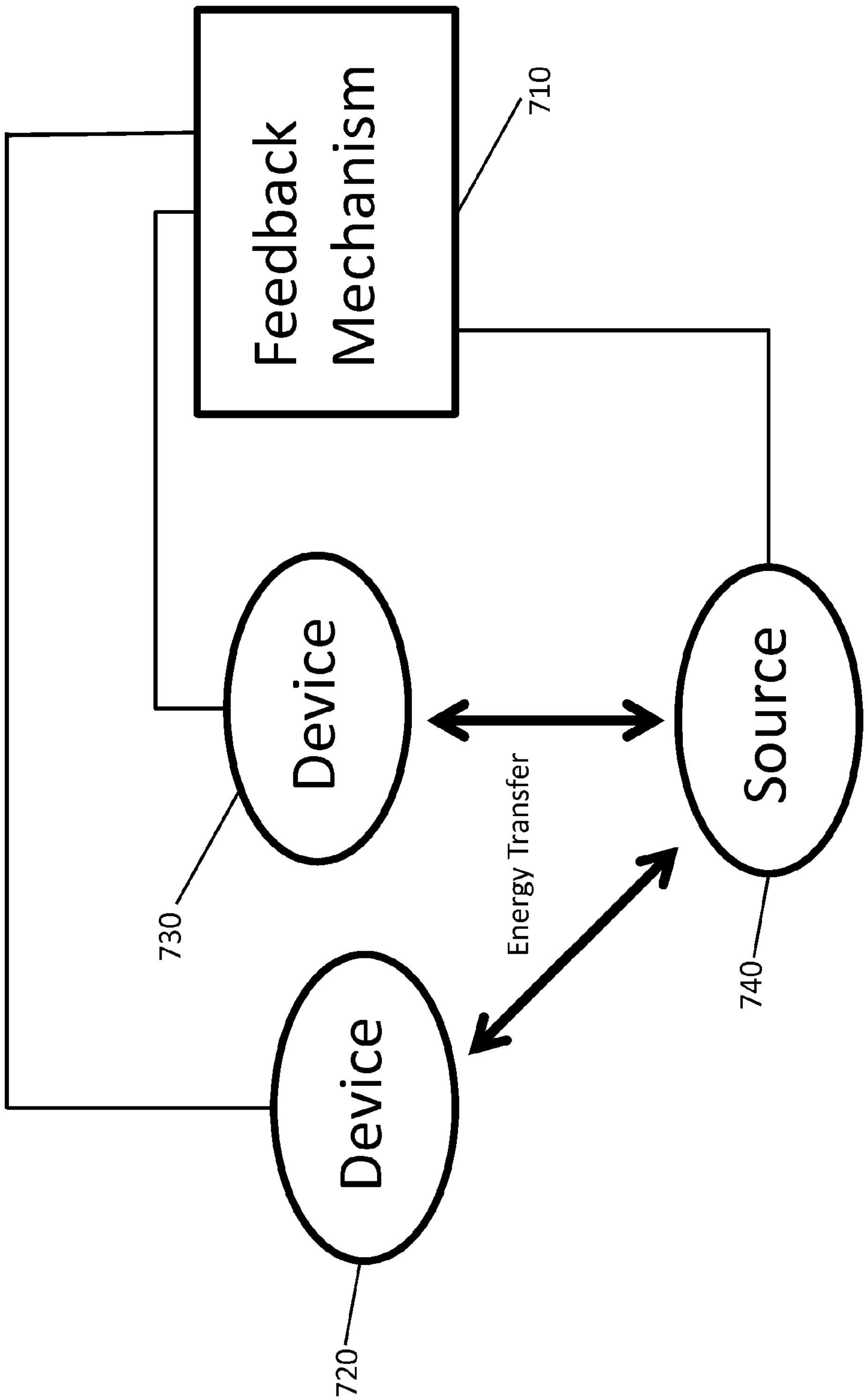
Feedback Mechanism
710
Device
730
Energy Transfer
Source
740
Device
720

FIG. 7

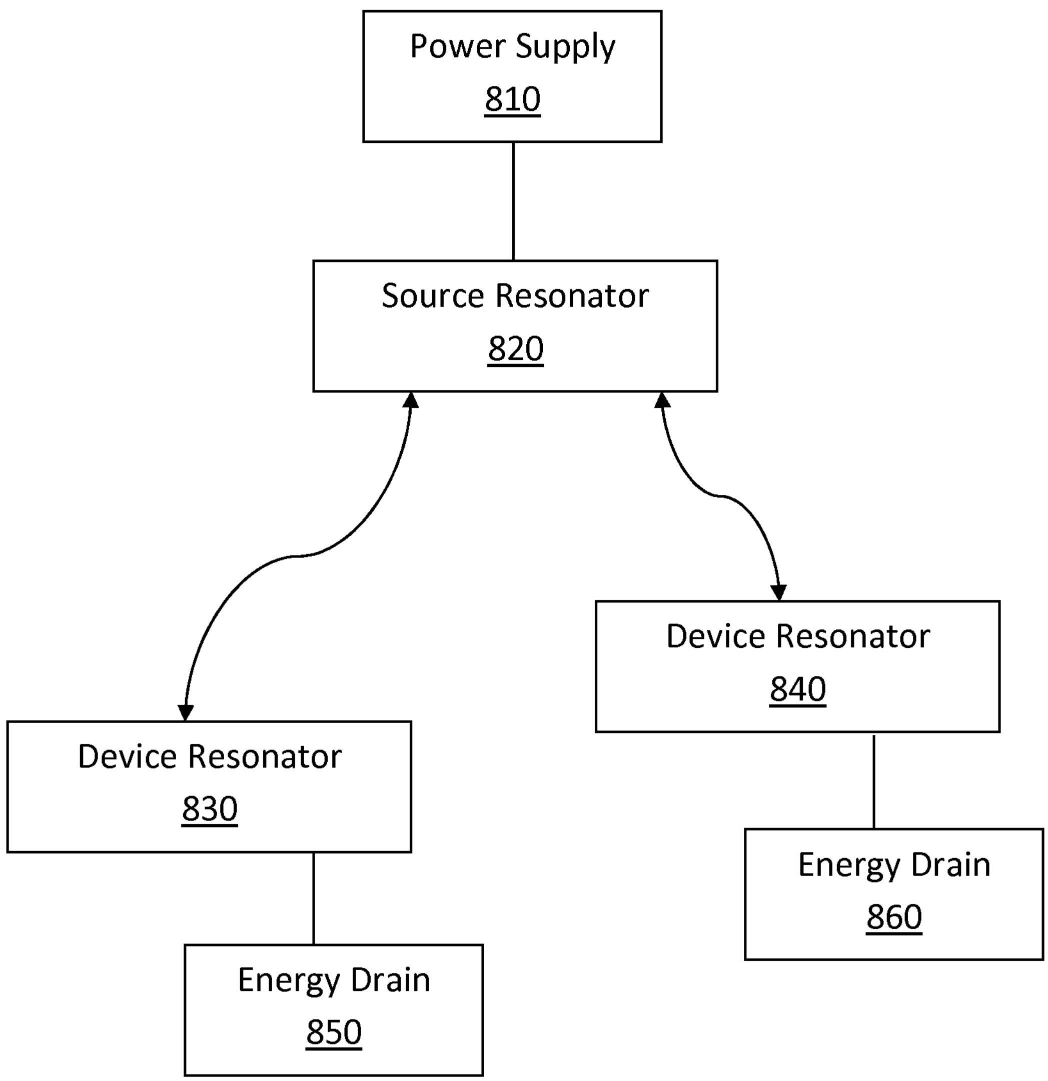
Power Supply
810
Source Resonator
820
Device Resonator
840
Device Resonator
830
Energy Drain
860
Energy Drain
850

FIG. 8

WIRELESS ENERGY TRANSFER WITH HIGH-Q TO MORE THAN ONE DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application entitled WIRELESS NON-RADIATIVE ENERGY TRANSFER filed on Sep. 3, 2009 having Ser. No. 12/553,957 ('957 Application), the entirety of which is incorporated herein by reference. The '957 Application is a continuation of U.S. patent application entitled WIRELESS NON-RADIATIVE ENERGY TRANSFER filed on Jul. 5, 2006 and having Ser. No. 11/481,077 ('077 Application), the entirety of which is incorporated herein by reference. The '077 Application claims the benefit of provisional application Ser. No. 60/698,442 filed Jul. 12, 2005 ('442 Application), the entirety of which is incorporated herein by reference.

This invention was made, in whole or in part by grant DMR-0213282 from the National Science Foundation. Accordingly, the Government may have certain rights in the invention.

BACKGROUND OF THE INVENTION

The invention relates to the field of oscillatory resonant electromagnetic modes, and in particular to oscillatory resonant electromagnetic modes, with localized slowly evanescent field patterns, for wireless non-radiative energy transfer.

In the early days of electromagnetism, before the electrical-wire grid was deployed, serious interest and effort was devoted towards the development of schemes to transport energy over long distances wirelessly, without any carrier medium. These efforts appear to have met with little, if any, 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 $L_{TRANS<<}L_{DEV}$, 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, the existing electrical-wire grid carries energy almost everywhere; even a medium-range wireless non-radiative energy transfer would be quite useful. One scheme currently used for some important applications relies on induction, but it is restricted to very close-range ($L_{TRANS}<<L_{DEV}$) energy transfers.

SUMMARY OF THE INVENTION

According to one aspect of the invention, there is provided an electromagnetic energy transfer device. The electromagnetic energy transfer device includes a first resonator structure receiving energy from an external power supply. The first resonator structure has a first Q-factor. A second resonator structure is positioned distal from the first resonator structure, and supplies useful working power to an external load. The second resonator structure has a second Q-factor. The distance between the two resonators can be larger than the characteristic size of each resonator. Non-radiative energy transfer between the first resonator structure and the second

resonator structure is mediated through coupling of their resonant-field evanescent tails.

According to another aspect of the invention, there is provided a method of transferring electromagnetic energy. The method includes providing a first resonator structure receiving energy from an external power supply. The first resonator structure has a first Q-factor. Also, the method includes a second resonator structure being positioned distal from the first resonator structure, and supplying useful working power to an external load. The second resonator structure has a second Q-factor. The distance between the two resonators can be larger than the characteristic size of each resonator. Furthermore, the method includes transferring non-radiative energy between the first resonator structure and the second resonator structure through coupling of their resonant-field evanescent tails.

In another aspect, a method of transferring energy is disclosed including the steps of providing a first resonator structure receiving energy from an external power supply, said first resonator structure having a first resonant frequency ω_1, and a first Q-factor Q_1, and characteristic size L_1. Providing a second resonator structure being positioned distal from said first resonator structure, at closest distance D, said second resonator structure having a second resonant frequency ω_2, and a second Q-factor Q_2, and characteristic size L_2, where the two said frequencies ω_1 and ω_2 are close to within the narrower of the two resonance widths Γ_1, and Γ_2, and transferring energy non-radiatively between said first resonator structure and said second resonator structure, said energy transfer being mediated through coupling of their resonant-field evanescent tails, and the rate of energy transfer between said first resonator and said second resonator being denoted by κ, where non-radiative means D is smaller than each of the resonant wavelengths λ_1 and λ_2, where c is the propagation speed of radiation in the surrounding medium.

Embodiments of the method may include any of the following features. In some embodiments, said resonators have $Q_1>100$ and $Q_2>100$, $Q_1>200$ and $Q_2>200$, $Q_1>500$ and $Q_2>500$, or even $Q_1>1000$ and $Q_2>1000$. In some such embodiments, $\kappa/\mathrm{sqrt}(\Gamma_1*\Gamma_2)$ may be greater than 0.2, greater than 0.5, greater than 1, greater than 2, or even grater than 5. In some such embodiments D/L_2 may be greater than 1, greater than 2, greater than 3, greater than 5.

In another aspect, an energy transfer device is disclosed which includes: a first resonator structure receiving energy from an external power supply, said first resonator structure having a first resonant frequency ω_1, and a first Q-factor Q_1, and characteristic size L_1, and a second resonator structure being positioned distal from said first resonator structure, at closest distance D, said second resonator structure having a second resonant frequency ω_2, and a second Q-factor Q_2, and characteristic size L_2.

The two said frequencies ω_1 and ω_2 are close to within the narrower of the two resonance widths Γ_1, and Γ_2. The non-radiative energy transfer between said first resonator structure and said second resonator structure is mediated through coupling of their resonant-field evanescent tails, and the rate of energy transfer between said first resonator and said second resonator is denoted by κ. The non-radiative means D is smaller than each of the resonant wavelengths λ_1 and λ_2, where c is the propagation speed of radiation in the surrounding medium.

Embodiments of the device may include any of the following features. In some embodiments, said resonators have $Q_1>100$ and $Q_2>100$, $Q_1>200$ and $Q_2>200$, $Q_1>500$ and $Q_2>500$, or even $Q_1>1000$ and $Q_2>1000$. In some such embodiments, $\kappa/\mathrm{sqrt}(\Gamma_1*\Gamma_2)$ may be greater than 0.2, greater than 0.5, greater than 1, greater than 2, or even grater than 5. In some such embodiments D/L_2 may be greater than 1, greater than 2, greater than 3, or even greater than 5.

In some embodiments, the resonant field in the device is electromagnetic.

In some embodiments, the first resonator structure includes a dielectric sphere, where the characteristic size L**1** is the radius of the sphere.

In some embodiments, the first resonator structure includes a metallic sphere, where the characteristic size L**1** is the radius of the sphere.

In some embodiments, the first resonator structure includes a metallodielectric sphere, where the characteristic size L**1** is the radius of the sphere.

In some embodiments, the first resonator structure includes a plasmonic sphere, where the characteristic size L**1** is the radius of the sphere.

In some embodiments, the first resonator structure includes a polaritonic sphere, where the characteristic size L**1** is the radius of the sphere.

In some embodiments, the first resonator structure includes a capacitively-loaded conducting-wire loop, where the characteristic size L**1** is the radius of the loop.

In some embodiments, the second resonator structure includes a dielectric sphere, where the characteristic size L**2** is the radius of the sphere.

In some embodiments, the second resonator structure includes a metallic sphere where the characteristic size L**2** is the radius of the sphere.

In some embodiments, the second resonator structure includes a metallodielectric sphere where the characteristic size L**2** is the radius of the sphere.

In some embodiments, the second resonator structure includes a plasmonic sphere where the characteristic size L**2** is the radius of the sphere.

In some embodiments, the second resonator structure includes a polaritonic sphere where the characteristic size L**2** is the radius of the sphere.

In some embodiments, the second resonator structure includes a capacitively-loaded conducting-wire loop where the characteristic size L**2** is the radius of the loop.

In some embodiments, the resonant field in the device is acoustic.

It is to be understood that embodiments of the above described methods and devices may include any of the above listed features, alone or in combination.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram illustrating an exemplary embodiment of the invention;

FIG. **2**A is a numerical FDTD result for a high-index disk cavity of radius r along with the electric field; FIG. **2**B a numerical FDTD result for a medium-distance coupling between two resonant disk cavities: initially, all the energy is in one cavity (left panel); after some time both cavities are equally excited (right panel).

FIG. **3** is schematic diagram demonstrating two capacitively-loaded conducting-wire loops;

FIGS. **4**A-**4**B are numerical FDTD results for reduction in radiation-Q of the resonant disk cavity due to scattering from extraneous objects;

FIG. **5** is a numerical FDTD result for medium-distance coupling between two resonant disk cavities in the presence of extraneous objects; and

FIGS. **6**A-**6**B are graphs demonstrating efficiencies of converting the supplied power into useful work (ηw), radiation and ohmic loss at the device (ηd), and the source(ηs), and dissipation inside a human (ηh), as a function of the coupling-to-loss ratio $\kappa/\Gamma d$; in panel (a) Γw is chosen so as to minimize the energy stored in the device, while in panel (b) Γw is chosen so as to maximize the efficiency ηw for each $\kappa/\Gamma d$.

FIG. **7** is a schematic diagram of a feedback mechanism to correct the resonators exchanging wireless energy for detuning because of the effect of an extraneous object.

FIG. **8** is a schematic diagram of an exemplary system in which a high-Q source resonator **810** is receiving power from a power supply **820** and wirelessly transfers non-radiative electromagnetic energy to multiple high-Q device resonators **830** and **840**, each of which is coupled to an energy drain **850** and **860**, respectively.

DETAILED DESCRIPTION OF THE INVENTION

In contrast to the currently existing schemes, the invention provides the feasibility of using long-lived oscillatory resonant electromagnetic modes, with localized slowly evanescent field patterns, for wireless non-radiative energy transfer. The basis of this technique is that two same-frequency resonant objects tend to couple, while interacting weakly with other off-resonant environmental objects. The purpose of the invention is to quantify this mechanism using specific examples, namely quantitatively address the following questions: up to which distances can such a scheme be efficient and how sensitive is it to external perturbations. Detailed theoretical and numerical analysis show that a mid-range (LTRANS≈few*LDEV) wireless energy-exchange can actually be achieved, while suffering only modest transfer and dissipation of energy into other off-resonant objects.

The omnidirectional by 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 a wired electricity network on the ceiling of a factory room, while devices, such as robots, vehicles, computers, or similar are roaming freely within the room. Other possible applications include electric-engine buses, RFIDs, and perhaps even nano-robots. Similarly, in some embodiments multiple sources can transfer energy to one or more device objects. For example, as explained at in the paragraph bridging pages 4-5 of U.S. Provisional Application No. 60/698,442 to which the present application claims benefit and which is incorporated by reference above, for certain applications having uneven power transfer to the device object as the distance between the device and the source changes, multiple sources can be strategically placed to alleviate the problem, and/or the peak amplitude of the source can be dynamically adjusted.

The range and rate of the inventive 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 the exchange of energy between resonant objects is a weak-coupling approach called "coupled-mode theory". FIG. **1** is a schematic diagram illustrating a general description of the invention. The invention uses a source and device to perform energy transferring. Both the source **1** and device **2** are resonator structures, and are separated a distance D from each other. In this arrangement, the electromagnetic field of the system of source **1** and device **2** is approximated by F(r,t)≈a**1**(t)F**1**(r)+a**2**(t)F**2**(r), where F**1**,**2**(r)=[E**1**,**2**(r) H**1**,**2**(r)] are the eigenmodes of source **1** and device **2** alone, and then the field amplitudes a**1**(t) and a**2**(t) can be shown to satisfy the "coupled-mode theory":

$$\frac{da_1}{dt} = -i(\omega_1 - i\Gamma_1)a_1 + i\kappa_{11}a_1 + i\kappa_{12}a_2 \quad (1)$$

$$\frac{da_2}{dt} = -i(\omega_2 - i\Gamma_2)a_2 + i\kappa_{22}a_2 + i\kappa_{21}a_1,$$

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, $\kappa_{12,21}$ are the coupling coefficients, and $\kappa_{11,22}$ model the shift in the complex frequency of each object due to the presence of the other.

The approach of Eq. 1 has been shown, on numerous occasions, to provide an excellent description of resonant phenomena for objects of similar complex eigen-frequencies (namely $|\omega_1-\omega_2|<<|\kappa_{12,21}|$ and $\Gamma_{19}\approx\Gamma_2$), whose resonances are reasonably well defined (namely $\Gamma_{1,2}$&$\text{Im}\{\kappa_{11,22}\}<<|\kappa_{12,21}|$) and in the weak coupling limit (namely $|\kappa_{12,21}|<<\omega_{1,2}$). Coincidentally, these requirements also enable optimal operation for energy transfer. Also, Eq. (1) show that the energy exchange can be nearly perfect at exact resonance ($\omega_1=\omega_2$ and $\Gamma_1=\Gamma_2$), and that the losses are minimal when the "coupling-time" is much shorter than all "loss-times". Therefore, the invention requires resonant modes of high $Q=\omega/(2\Gamma)$ for low intrinsic-loss rates $\Gamma_{1,2}$, and with evanescent tails significantly longer than the characteristic sizes L_1 and L_2 of the two objects for strong coupling rate $|\kappa_{12,21}|$ over large distances D, where D is the closest distance between the two objects. This is a regime of operation that has not been studied extensively, since one usually prefers short tails, to minimize interference with nearby devices.

Objects of nearly infinite extent, such as dielectric waveguides, can support guided modes whose evanescent tails are decaying exponentially in the direction away from the object, slowly if tuned close to cutoff, and can have nearly infinite Q. To implement the inventive energy-transfer scheme, such geometries might be suitable for certain applications, but usually finite objects, namely ones that are topologically surrounded everywhere by air, are more appropriate.

Unfortunately, objects of finite extent cannot support electromagnetic states that are exponentially decaying in all directions in air, since in free space: $\vec{k}^2=\omega^2/c^2$. Because of this, one can show that they cannot support states of infinite Q. However, very long-lived (so-called "high-Q") states can be found, whose tails display the needed exponential-like decay away from the resonant object over long enough distances before they turn oscillatory (radiative). The limiting surface, where this change in the field behavior happens, is called the "radiation caustic", and, for the wireless energy-transfer scheme to be based on the near field rather than the far/radiation field, the distance between the coupled objects must be such that one lies within the radiation caustic of the other.

The invention is very general and any type of resonant structure satisfying the above requirements can be used for its implementation. As examples and for definiteness, one can 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 fairly good performance. Their difference lies mostly in the frequency range of applicability due to practical considerations, for example, in the optical regime dielectrics prevail, since conductive materials are highly lossy.

Consider a 2D dielectric disk cavity of radius r and permittivity ∈ surrounded by air that supports high-Q whispering-gallery modes, as shown in FIG. **2**A. Such a cavity is studied using both analytical modeling, such as separation of variables in cylindrical coordinates and application of boundary conditions, and detailed numerical finite-difference-time-domain (FDTD) simulations with a resolution of 30 pts/r. Note that the physics of the 3D case should not be significantly different, while the analytical complexity and numerical requirements would be immensely increased. The results of the two methods for the complex eigen-frequencies and the field patterns of the so-called "leaky" eigenmodes are in an excellent agreement with each other for a variety of geometries and parameters of interest.

The radial modal decay length, which determines the coupling strength $\kappa\equiv|\kappa_{21}|=|\kappa_{12}|$, is on the order of the wavelength, therefore, for near-field coupling to take place between cavities whose distance is much larger than their size, one needs subwavelength-sized resonant objects ($m<<\lambda$). High-radiation-Q and long-tailed subwavelength resonances can be achieved, when the dielectric permittivity ∈ is as large as practically possible and the azimuthal field variations (of principal number m) are slow (namely m is small).

One such TE-polarized dielectric-cavity mode, which has the favorable characteristics $Q_{rad}=1992$ and $\lambda/r=20$ using $\in=147.7$ and m=2, is shown in FIG. **2**A, and will be the "test" cavity **18** for all subsequent calculations for this class of resonant objects. Another example of a suitable cavity has $Q_{rad}=9100$ and $\lambda/r=10$ using $\in=65.61$ and m=3. These values of s might at first seem unrealistically large. However, not only are there in the microwave regime (appropriate for meter-range coupling applications) many materials that have both reasonably high enough dielectric constants and low losses, for example, Titania: $\in\approx96$, $\text{Im}\{\in\}/\in\approx10^{-3}$; Barium tetratitanate: $\in\approx37$, $\text{Im}\{\in\}/\in\approx10^{-4}$; Lithium tantalite: $\in\approx40$, $\text{Im}\{\in\}/\in\approx10^{-4}$; etc.), but also ∈ could instead signify the effective index of other known subwavelength ($\lambda/r<<1$) surface-wave systems, such as surface-plasmon modes on surfaces of metal-like (negative-∈) materials or metallodielectric photonic crystals.

With regards to material absorption, typical loss tangents in the microwave (e.g. those listed for the materials above) suggest that $Q_{abs}\sim\in/\text{Im}\{\in\}\sim10000$. Combining the effects of radiation and absorption, the above analysis implies that for a properly designed resonant device-object d a value of $Q_d\sim2000$ should be achievable. Note though, that the resonant source s will in practice often be immobile, and the restrictions on its allowed geometry and size will typically be much less stringent than the restrictions on the design of the device; therefore, it is reasonable to assume that the radiative losses can be designed to be negligible allowing for $Q_s\sim10000$, limited only by absorption.

To calculate now the achievable rate of energy transfer, one can place two of the cavities **20**, **22** at distance D between their centers, as shown in FIG. **2**B. The normal modes of the combined system are then an even and an odd superposition of the initial modes and their frequencies are split by the coupling coefficient κ, which we want to calculate. Analytically, coupled-mode theory gives for dielectric objects $\kappa_{12}=\omega_2/2\cdot\int d^3rE_1^*(r)E_2(r)\in_1(r)/\int d^3r|E_1(r)|^2\in(r)$, where $\in_{1,2}(r)$ denote the dielectric functions of only object **1** alone or **2** alone excluding the background dielectric (free space) and ∈(r) the dielectric function of the entire space with both objects present. Numerically, one can find κ using FDTD simulations either by exciting one of the cavities and calculating the energy-transfer time to the other or by determining the split normal-mode frequencies. For the "test" disk cavity the radius r_C of the radiation caustic is $r_C \approx 11r$, and for non-radiative coupling $D<r_C$, therefore here one can choose D/r=10, 7, 5, 3. Then, for the mode of FIG. **3**, which is odd with respect to the line that connects the two cavities, the analytical predictions are $\omega/2\kappa$=1602, 771, 298, 48, while the numerical predictions are $\omega/2\kappa$=1717, 770, 298, 47 respectively, so the two methods agree well. The radiation fields of the two initial cavity modes interfere constructively or destructively depending on their relative phases and amplitudes, leading to increased or decreased net radiation loss respectively, therefore for any cavity distance the even and odd normal modes have Qs that are one larger and one smaller than the initial single-cavity Q=1992 (a phenomenon not captured by coupled-mode theory), but in a way that the average Γ is always approximately $\Gamma \approx \omega/2Q$. Therefore, the corresponding coupling-to-loss ratios are κ/Γ=1.16, 2.59, 6.68, 42.49, and although they do not fall in the ideal operating regime $\kappa/\Gamma \gg 1$, the achieved values are still large enough to be useful for applications.

Consider a loop **10** or **12** of N coils of radius r of conducting wire with circular cross-section of radius a surrounded by air, as shown in FIG. **3**. This wire has inductance $L=\mu_O N^2 r[\ln(8r/a)-2]$, where μ_O is the magnetic permeability of free space, so connecting it to a capacitance C will make the loop resonant at frequency $\omega=1/\sqrt{LC}$. 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 inside the wire and radiative loss into free space.

For non-radiative coupling one should use the near-field region, whose extent is set roughly by the wavelength λ, therefore the preferable operating regime is that where the loop is small ($r \ll \lambda$). In this limit, the resistances associated with the two loss channels are respectively $R_{ohm}=\sqrt{\mu_O \rho \omega/2}\cdot Nr/a$ and $R_{rad}=\pi/6\cdot\eta_O N^2(\omega r/c)^4$, where ρ is the resistivity of the wire material and $\eta_O \approx 120\pi\ \Omega$ is the impedance of free space. The quality factor of such a resonance is then $Q=\omega L/(R_{ohm}+R_{rad})$ and is highest for some frequency determined by the system parameters: at lower frequencies it is dominated by ohmic loss and at higher frequencies by radiation.

To get a rough estimate in the microwave, one can use one coil (N=1) of copper ($\rho=1.69\cdot10^{-8}\ \Omega$m) wire and then for r=1 cm and a=1 mm, appropriate for example for a cell phone, the quality factor peaks to Q=1225 at f=380 MHz, for r=30 cm and a=2 mm for a laptop or a household robot Q=1103 at f=17 MHz, while for r=1 m and a=4 mm (that could be a source loop on a room ceiling) Q=1315 at f=5 MHz. So in general, expected quality factors are Q≈1000-1500 at $\lambda/r \approx$50-80, namely suitable for near-field coupling.

The rate for energy transfer between two loops **10** and **12** at distance D between their centers, as shown in FIG. **3**, is given by $\kappa_{12}=\omega M/2\sqrt{L_1 L_2}$, where M is the mutual inductance of the two loops **10** and **12**. In the limit $r \ll D \ll \lambda$ one can use the quasi-static result $M=\pi/4\cdot\mu_O N_1 N_2 (r_1 r_2)^2/D^3$, which means that $\omega/2\kappa \sim (D/\sqrt{r_1 r_2})^3$. For example, by choosing again D/r=10, 8, 6 one can get for two loops of r=1 cm, same as used before, that $\omega/2\kappa$=3033, 1553, 655 respectively, for the r=30 cm that $\omega/2\kappa$=7131, 3651, 1540, and for the r=1 m that $\omega/2\kappa$=6481, 3318, 1400. The corresponding coupling-to-loss ratios peak at the frequency where peaks the single-loop Q and are κ/F=0.4, 0.79, 1.97 and 0.15, 0.3, 0.72 and 0.2, 0.4, 0.94 for the three loop-kinds and distances. An example of dissimilar loops is that of a r=1 m (source on the ceiling) loop and a r=30 cm (household robot on the floor) loop at a distance D=3 m (room height) apart, for which $\kappa/\sqrt{\Gamma_1\Gamma_2}$=0.88 peaks at f=6.4 MHz, in between the peaks of the individual Q's. Again, these values are not in the optimal regime $\kappa/\Gamma \ll 1$, but will be shown to be sufficient.

It is important to appreciate the difference between this inductive scheme and the already used close-range inductive schemes for energy transfer in that those schemes are non-resonant. Using coupled-mode theory it is easy to show that, keeping the geometry and the energy stored at the source fixed, the presently proposed resonant-coupling inductive mechanism allows for Q approximately 1000 times more power delivered for work at the device than the traditional non-resonant mechanism, and this is why mid-range energy transfer is now possible. Capacitively-loaded conductive loops are actually being widely used as resonant antennas (for example in cell phones), but those operate in the far-field regime with $r/\lambda \sim 1$, and the radiation Q's are intentionally designed to be small to make the antenna efficient, so they are not appropriate for energy transfer.

Clearly, the success of the inventive 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 interaction of an extraneous object with a resonant object can be obtained by a modification of the coupled-mode-theory model in Eq. (1), since the extraneous object either does not have a well-defined resonance or is far-off-resonance, the energy exchange between the resonant and extraneous objects is minimal, so the term κ_{12} in Eq. (1) can be dropped. The appropriate analytical model for the field amplitude in the resonant object $a_1(t)$ becomes:

$$\frac{da_1}{dt} = -i(\omega_1 - i\Gamma_1)a_1 + i\kappa_{11}a_1 \tag{2}$$

Namely, the effect of the extraneous object is just a perturbation on the resonance of the resonant object and it is two-fold: First, it shifts its resonant frequency through the real part of κ_{11} thus detuning it from other resonant objects. As shown in FIG. **7**, this is a problem that can be fixed rather easily by applying a feedback mechanism **710** to every device (e.g., device resonators **720** and **730**) that corrects its frequency, such as through small changes in geometry, and matches it to that of the source resonator **740**. Second, it forces the resonant object to lose modal energy due to scattering into radiation from the extraneous object through the induced polarization or currents in it, and due to material absorption in the extraneous object through the imaginary part of κ_{11}. This reduction in Q can be a detrimental effect to the functionality of the energy-transfer scheme, because it cannot be remedied, so its magnitude must be quantified.

In the first example of resonant objects that have been considered, the class of dielectric disks, small, low-index, low-material-loss or far-away stray objects will induce small scattering and absorption. To examine realistic cases that are more dangerous for reduction in Q, one can therefore place the "test" dielectric disk cavity **40** close to: a) another off-resonance object **42**, such as a human being, of large Re{∈}=49 and Im{∈}=16 and of same size but different shape, as shown in FIG. **4**A; and b) a roughened surface **46**, such as a wall, of large extent but of small Re{∈}=2.5 and Im{∈}=0.05, as shown in FIG. **4**B.

Analytically, for objects that interact with a small perturbation the reduced value of radiation-Q due to scattering could be estimated using the polarization $\int d^3r|P_{X1}(r)|^2 \propto \int d^3r|E_1(r)\cdot Re\{\in_X(r)\}|^2$ induced by the resonant cavity **1** inside the extraneous object X=42 or roughened surface X=46. Since in the examined cases either the refractive index or the size of the extraneous objects is large, these first-order perturbation-theory results would not be accurate enough, thus one can only rely on numerical FDTD simulations. The absorption-Q inside these objects can be estimated through $Im\{\kappa_{11}\}=\omega_1/2\cdot\int d^3r|E_1(r)|^2 Im\{\in_X(r)\}/\int d^3r|E_1(r)|^2\in(r)$.

Using these methods, for distances D/r=10, 7, 5, 3 between the cavity and extraneous-object centers one can find that Q_{rad}=1992 is respectively reduced to Q_{rad}=1988, 1258, 702, 226, and that the absorption rate inside the object is Q_{abs}=312530, 86980, 21864, 1662, namely the resonance of the cavity is not detrimentally disturbed from high-index and/or high-loss extraneous objects, unless the (possibly mobile) object comes very close to the cavity. For distances D/r=10, 7, 5, 3, 0 of the cavity to the roughened surface we find respectively Q_{rad}=2101, 2257, 1760, 1110, 572, and Q_{abs}>4000, namely the influence on the initial resonant mode is acceptably low, even in the extreme case when the cavity is embedded on the surface. Note that a close proximity of metallic objects could also significantly scatter the resonant field, but one can assume for simplicity that such objects are not present.

Imagine now a combined system where a resonant source-object s is used to wirelessly transfer energy to a resonant device-object d but there is an off-resonance extraneous-object e present. One can see that the strength of all extrinsic loss mechanisms from e is determined by $|E_s(r_e)|^2$, by the square of the small amplitude of the tails of the resonant source, evaluated at the position r_e of the extraneous object. In contrast, the coefficient of resonant coupling of energy from the source to the device is determined by the same-order tail amplitude $|E_s(r_d)|$, evaluated at the position r_d of the device, but this time it is not squared! Therefore, for equal distances of the source to the device and to the extraneous object, the coupling time for energy exchange with the device is much shorter than the time needed for the losses inside the extraneous object to accumulate, especially if the amplitude of the resonant field has an exponential-like decay away from the source. One could actually optimize the performance by designing the system so that the desired coupling is achieved with smaller tails at the source and longer at the device, so that interference to the source from the other objects is minimal

The above concepts can be verified in the case of dielectric disk cavities by a simulation that combines FIGS. **2A-2**B and **4A-4**B, namely that of two (source-device) "test" cavities **50** placed **10***r* apart, in the presence of a same-size extraneous object **52** of ∈=49 between them, and at a distance **5***r* from a large roughened surface **56** of ∈=2.5, as shown in FIG. **5**. Then, the original values of Q=1992, ω/2κ=1717 (and thus κ/Γ=1.16) deteriorate to Q=765, ω/2κ=965 (and thus κ/Γ=0.79). This change is acceptably small, considering the extent of the considered external perturbation, and, since the system design has not been optimized, the final value of coupling-to-loss ratio is promising that this scheme can be useful for energy transfer.

In the second example of resonant objects being considered, the conducting-wire loops, the influence of extraneous objects on the resonances is nearly absent. The reason for this is that, in the quasi-static regime of operation (r<<λ) that is being considered, the near field in the air region surrounding the loop is predominantly magnetic, since the electric field is localized inside the capacitor. Therefore, extraneous objects 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 common 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. The only perturbation that is expected to affect these resonances is a close proximity of large metallic structures.

An extremely important implication of the above fact relates to safety considerations for human beings. Humans are also non-magnetic and can sustain strong magnetic fields without undergoing any risk. This is clearly an advantage of this class of resonant systems for many real-world applications. On the other hand, dielectric systems of high (effective) index have the advantages that their efficiencies seem to be higher, judging from the larger achieved values of κ/Γ, and that they are also applicable to much smaller length-scales, as mentioned before.

Consider now again the combined system of resonant source s and device d in the presence of a human h and a wall, and now let us study the efficiency of this resonance-based energy-transfer scheme, when energy is being drained from the device for use into operational work. One can use the parameters found before: for dielectric disks, absorption-dominated loss at the source $Q_s\sim10^4$, radiation-dominated loss at the device $Q_d\sim10^3$ (which includes scattering from the human and the wall), absorption of the source- and device-energy at the human Q_{s-h}, $Q_{d-h}\sim10^4$-10^5 depending on his/her not-very-close distance from the objects, and negligible absorption loss in the wall; for conducting-wire loops, $Q_s\sim Q_d\sim10^3$, and perturbations from the human and the wall are negligible. With corresponding loss-rates Γ=ω/2Q, distance-dependent coupling κ, and the rate at which working power is extracted Γ_w, the coupled-mode-theory equation for the device field-amplitude is

$$\frac{da_d}{dt} = -i(\omega - i\Gamma_d)a_d + i\kappa a_s - \Gamma_{d-h}a_d - \Gamma_w a_d. \tag{3}$$

Different temporal schemes can be used to extract power from the device and their efficiencies exhibit different dependence on the combined system parameters. Here, one can assume steady state, such that the field amplitude inside the source is maintained constant, namely $a_s(t)=A_s e^{-i\omega t}$, so then the field amplitude inside the device is $a_d(t)=A_d e^{-i\omega t}$ with $A_d=i\kappa/(\Gamma_d+\Gamma_{d-h}+\Gamma_w)A_s$. Therefore, the power lost at the source is $P_s=2\Gamma_s|A_s|^2$, at the device it is $P_d=2\Gamma_d|A_d|^2$, the power absorbed at the human is $P_h=2\Gamma_{s-h}|A_s|^2+2\Gamma_{d-h}|A_d|^2$, and the useful extracted power is $P_w=2\Gamma_w|A_d|^2$. From energy conservation, the total power entering the system is $P_{total}=P_s+P_d+P_h+P_w$. Denote the total loss-rates $\Gamma_s^{tot}=\Gamma_s+\Gamma_{s-h}$ and $\Gamma_d^{tot}=\Gamma_d+\Gamma_{d-h}$. Depending on the targeted application, the work-drainage rate should be chosen either $\Gamma_w=\Gamma_d^{tot}$ minimize the required energy stored in the resonant objects or $\Gamma_w=\Gamma_d^{tot}\sqrt{1+\kappa^2/\Gamma_s^{tot}\Gamma_d^{tot}}>\Gamma_d^{tot}$ such that the ratio of useful-to-lost powers, namely the efficiency $\eta_w=P_w/P_{total}$, is maximized for some value of κ. The efficiencies η for the two different choices are shown in FIGS. **6**A and **6**B respectively, as a function of the κ/Γ_d figure-of-merit which in turn depends on the source-device distance.

FIGS. **6**A-**6**B show that for the system of dielectric disks and the choice of optimized efficiency, the efficiency can be large, e.g., at least 40%. The dissipation of energy inside the human is small enough, less than 5%, for values $\kappa/\Gamma_d>1$ and

$Q_h > 10^5$, namely for medium-range source-device distances ($D_d/r<10$) and most human-source/device distances ($D_h/r>8$). For example, for $D_d/r=10$ and $D_h/r=8$, if 10W must be delivered to the load, then, from FIG. **6**B, ~0.4 W will be dissipated inside the human, ~4 W will be absorbed inside the source, and ~2.6 W will be radiated to free space. For the system of conducting-wire loops, the achieved efficiency is smaller, ~20% for $\kappa/\Gamma_d \approx 1$, but the significant advantage is that there is no dissipation of energy inside the human, as explained earlier.

Even better performance should be achievable through optimization of the resonant object designs. Also, by exploiting the earlier mentioned interference effects between the radiation fields of the coupled objects, such as continuous-wave operation at the frequency of the normal mode that has the larger radiation-Q, one could further improve the overall system functionality. Thus the inventive wireless energy-transfer scheme is promising for many modern applications. Although all considerations have been for a static geometry, all the results can be applied directly for the dynamic geometries of mobile objects, since the energy-transfer time κ^{-1}~1 μs, which is much shorter than any timescale associated with motions of macroscopic objects.

The invention provides a resonance-based scheme for mid-range wireless non-radiative energy transfer. Analyses of very simple implementation geometries provide encouraging performance characteristics for the potential applicability of the proposed mechanism. For example, in the macroscopic world, this scheme could 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 else to transfer energy to autonomous nano-objects, without worrying much about the relative alignment between the sources and the devices; energy-transfer distance could be even longer compared to the objects' size, since $\mathrm{Im}\{\in(\kappa)\}$ of dielectric materials can be much lower at the required optical frequencies than it is at microwave frequencies. Accordingly, FIG. **8** is a schematic drawing showing an exemplary system in which a high-Q source resonator **810** is receiving power from a power supply **820** and wirelessly transfers non-radiative electromagnetic energy to multiple high-Q device resonators **830** and **840**, each of which is coupled to an energy drain **850** and **860**, respectively.

As a venue of future scientific research, different material systems should be investigated for enhanced performance or different range of applicability. For example, it might be possible to significantly improve performance by exploring plasmonic systems. These systems can often have spatial variations of fields on their surface that are much shorter than the free-space wavelength, and it is precisely this feature that enables the required decoupling of the scales: the resonant object can be significantly smaller than the exponential-like tails of its field. Furthermore, one should also investigate using acoustic resonances for applications in which source and device are connected via a common condensed-matter object.

Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, may be made therein, without departing from the spirit and scope of the invention.

What is claimed is:

1. A system, comprising:

a source resonator having a resonant frequency ω_1, an intrinsic loss rate Γ_1, and capable of storing electromagnetic energy with a high intrinsic quality factor $Q_1=\omega_1/(2\Gamma_1)$, the source resonator configured to be coupled to an energy source;

a second resonator having a resonant frequency ω_2, an intrinsic loss rate Γ_2, and capable of storing electromagnetic energy with a high intrinsic quality factor $Q_2=\omega_2/(2\Gamma_2)$, the second resonator located a distance from the source resonator; and

a third resonator having a resonant frequency ω_3, an intrinsic loss rate Γ_2, and capable of storing electromagnetic energy with a high intrinsic quality factor $Q_3=\omega_3/(2\Gamma_3)$, the third resonator located a distance from the source resonator,

wherein the source resonator and at least one of the second resonator and third resonator are configured to be coupled to wirelessly transfer electromagnetic energy from said source resonator to said at least one of the second resonator and third resonator when the source resonator is coupled to the energy source, and

wherein $Q_1>100$ and $Q_2>100$,

wherein the resonators are movable relative to one another and wherein the wireless energy transfer occurs over a range of distances, and

wherein $\kappa/\sqrt{\Gamma_1\Gamma_2}>0.2$ over the range of distances, wherein κ is the wireless energy transfer rate.

2. The system of claim **1**, further comprising the energy source coupled to the source resonator.

3. The system of claim **1**, further comprising an energy drain configured to be coupled to the second resonator and an energy drain configured to be coupled to the third resonator.

4. The system of claim **3**, wherein at least one of the energy drains comprises a robot, vehicle, computer, cell phone, or a portable electronic device.

5. The system of claim **4**, wherein the at least one of the second resonator and third resonator is configured to provide useful power to the energy drain based on wirelessly transferred electromagnetic energy.

6. The system of claim **1**, wherein each intrinsic loss rate comprises a resistive component and a radiative component.

7. The system of claim **1**, wherein the source resonator is electromagnetically coupled to each of the second and third resonators.

8. The system of claim **7**, wherein the source resonator is configured to wirelessly transfer electromagnetic energy from the source resonator to each of the second and third resonators.

9. The system of claim **1**, wherein $Q_3>100$.

10. The system of claim **1**, wherein at least one of the resonators is tunable.

11. The system of claim **1**, wherein the range of distances includes 5 cm.

12. The system of claim **1**, wherein the range of distances includes 10 cm.

13. The system of claim **1**, wherein the range of distances includes 30 cm.

14. The system of claim **1**, wherein $\kappa/\sqrt{\Gamma_2\Gamma_2}>0.5$ over the range of distances.

15. The system of claim **1**, wherein $\kappa/\sqrt{\Gamma_1\Gamma_2}>1$ over the range of distances.

16. The system of claim **1**, wherein the efficiency of the wireless energy transfer is at least 20% over the range of distances.

17. The system of claim 1, wherein frequencies $f_1=\omega_1/2\pi$, $f_2=\omega_2/2\pi$, and $f_3=\omega_3/2\pi$ of the resonators are each at least 5 MHz.

18. The system of claim 1, further comprising a feedback mechanism coupled to at least one of the resonators to correct for detuning to correct for detuning of the resonant frequencies.

19. The system of claim 1, wherein the energy source is coupled to the source resonator, an energy drain is coupled to the second resonator, and the source resonator is electromagnetically coupled to the second resonator, and wherein the energy source and energy drain are configured to be driven to increase the ratio of useful-to-lost power for varying wireless energy transfer rates κ between the source resonator and the second resonator.

20. The system of claim 1, wherein the source resonator is electromagnetically coupled to the second resonator, and wherein the source resonator and second resonator are configured to be adjustably tuned to increase the ratio of useful-to-lost power for varying wireless energy transfer rates κ between the source resonator and the second resonator.

21. The system of claim 1, wherein the source resonator and the second resonator have different characteristic sizes.

22. The system of claim 1, wherein $f_1=\omega_1/(2\pi)$, $f_2=\omega_2/(2\pi)$, and $f_3=\omega_3/(2\pi)$, and each of f_1, f_2, and f_3 is between about 5 MHz and 380 MHz.

23. A method, comprising:

providing a source resonator having a resonant frequency ω_1, an intrinsic loss rate Γ_1, and capable of storing electromagnetic energy with a high intrinsic quality factor $Q_1=\omega_1/(2\Gamma_1)$, the source resonator configured to be coupled to an energy source;

providing a second resonator having a resonant frequency ω_2, an intrinsic loss rate Γ_2, and capable of storing electromagnetic energy with a high intrinsic quality factor $Q_2=\omega_2/(2\Gamma_2)$, the second resonator located a distance from the source resonator; and

providing a third resonator having a resonant frequency ω_3, an intrinsic loss rate Γ_3, and capable of storing electromagnetic energy with a high intrinsic quality factor $Q_3=\omega_3/(2\Gamma_3)$, the third resonator located a distance from the source resonator,

wherein the source resonator and at least one of the second resonator and third resonator are configured to be coupled to wirelessly transfer electromagnetic energy from said source resonator to said at least one of the second resonator and third resonator when the source resonator is coupled to the energy source,

wherein $Q_1>100$ and $Q_2>100$,

wherein the resonators are movable relative to one another and wherein the wireless energy transfer occurs over a range of distances, and

wherein $\kappa/\sqrt{\Gamma_1\Gamma_2}>0.2$ over the range of distances, wherein κ is the wireless energy transfer rate.

24. The method of claim 23, wherein the source resonator and the second resonator have different characteristic sizes.

25. The method of claim 23, wherein the source resonator is electromagnetically coupled to the second resonator, and wherein the source resonator and second resonator are adjustably tuned to increase the ratio of useful-to-lost power for varying wireless energy transfer rates κ between the source resonator and the second resonator.

26. The method of claim 23, wherein the energy source is coupled to the source resonator.

27. The method of claim 23, wherein an energy drain is coupled to the second resonator and an energy drain is coupled to the third resonator.

28. The method of claim 27, wherein at least one of the energy drains comprises a robot, vehicle, computer, cell phone, or a portable electronic device.

29. The method of claim 27, wherein the at least one of the second resonator and third resonator is configured to provide useful power to the energy drain based on wirelessly transferred electromagnetic energy.

30. The method of claim 23, wherein each intrinsic loss rate comprises a resistive component and a radiative component.

31. The method of claim 23, wherein the source resonator is electromagnetically coupled to each of the second and third resonators.

32. The method of claim 31, wherein the source resonator is configured to wirelessly transfer electromagnetic energy from the source resonator to each of the second and third resonators.

33. The method of claim 23, wherein $Q_3>100$.

34. The method of claim 23, wherein at least one of the resonators is tunable.

35. The method of claim 23, wherein the range of distances includes 5 cm.

36. The method of claim 23, wherein the range of distances includes 10 cm.

37. The method of claim 23, wherein the range of distances includes 30 cm.

38. The method of claim 23, wherein $\kappa/\sqrt{\Gamma_1\Gamma_2}>0.5$ over the range of distances.

39. The method of claim 23, wherein $\kappa/\sqrt{\Gamma_1\Gamma_2}>1$ over the range of distances.

40. The method of claim 23, wherein the efficiency of the wireless energy transfer is at least 20% over the range of distances.

41. The method of claim 23, wherein frequencies $f_1=\omega_1/2\pi$, $f_2=\omega_2/2\pi$, and $f_3=\omega_3/2\pi$ of the resonators are each at least 5 MHz.

42. The method of claim 23, wherein a feedback mechanism is coupled to at least one of the resonators to correct for detuning to correct for detuning of the resonant frequencies.

43. The method of claim 23, wherein the energy source is coupled to the source resonator, an energy drain is coupled to the second resonator, and the source resonator is electromagnetically coupled to the second resonator, and wherein the energy source and energy drain is driven to increase the ratio of useful-to-lost power for varying wireless energy transfer rates κ between the source resonator and the second resonator.

44. The method of claim 23, wherein $f_1=\omega_1/(2\pi)$, $f_2=\omega_2/(2\pi)$, and $f_3=\omega_3/(2\pi)$, and each of f_1, f_2, and f_3 is between about 5 MHz and 380 MHz.

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