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(54) **FOREIGN OBJECT DETECTION IN WIRELESS ENERGY TRANSFER SYSTEMS**

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(56) **References Cited**

U.S. PATENT DOCUMENTS

645,576 A	3/1900	Tesla
649,621 A	5/1900	Tesla

(Continued)

FOREIGN PATENT DOCUMENTS

CA	142352	8/1912
CN	101807822	8/2010

(Continued)

OTHER PUBLICATIONS

Supplementary European Search Report for European Application No. EP 12 83 0255 dated Apr. 8, 2015 (3 pages).

(Continued)

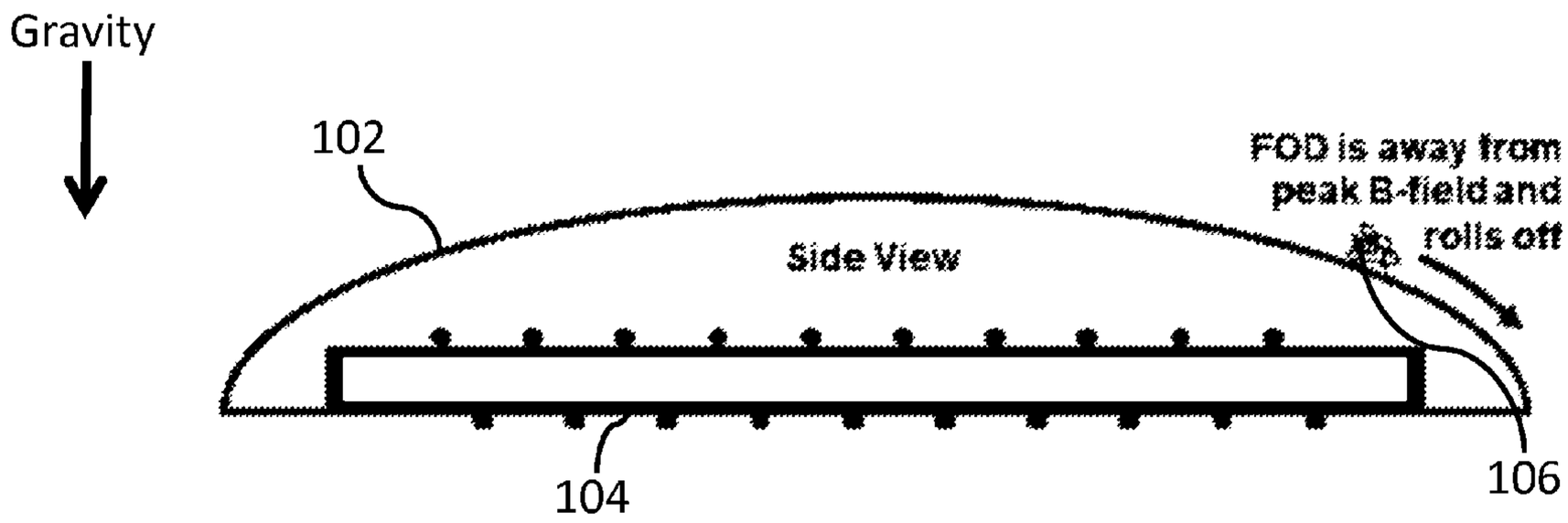
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(57) **ABSTRACT**

A wireless energy transfer system includes a foreign object debris detection system. The system includes at least one wireless energy transfer source configured to generate an oscillating magnetic field. The foreign object debris may be detected by at least one field gradiometer positioned in the oscillating magnetic field. The voltage of the at least one field gradiometer may be measured using readout circuitry and a feedback loop based on the readings from the gradiometers may be used to control the parameters of the wireless energy source.

18 Claims, 10 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

787,412	A	4/1905	Tesla
1,119,732	A	12/1914	Tesla
2,133,494	A	10/1938	Waters
3,517,350	A	6/1970	Beaver
3,535,543	A	10/1970	Dailey
3,780,425	A	12/1973	Penn et al.
3,871,176	A	3/1975	Schukei
4,088,999	A	5/1978	Fletcher et al.
4,095,998	A	6/1978	Hanson
4,180,795	A	12/1979	Matsuda et al.
4,280,129	A	7/1981	Wells
4,450,431	A	5/1984	Hochstein
4,588,978	A	5/1986	Allen
4,843,259	A	6/1989	Weisshaupt
5,027,709	A	7/1991	Slagle
5,033,295	A	7/1991	Schmid et al.
5,034,658	A	7/1991	Hiering et al.
5,053,774	A	10/1991	Schuermann et al.
5,070,293	A	12/1991	Ishii et al.
5,118,997	A	6/1992	El-Hamamsy
5,216,402	A	6/1993	Carosa
5,229,652	A	7/1993	Hough
5,287,112	A	2/1994	Schuermann
5,341,083	A	8/1994	Klontz et al.
5,367,242	A	11/1994	Hulman
5,374,930	A	12/1994	Schuermann
5,408,209	A	4/1995	Tanzer et al.
5,437,057	A	7/1995	Richley et al.
5,455,467	A	10/1995	Young et al.
5,493,691	A	2/1996	Barrett
5,522,856	A	6/1996	Reineman
5,528,113	A	6/1996	Boys et al.
5,541,604	A	7/1996	Meier
5,550,452	A	8/1996	Shirai et al.
5,565,763	A	10/1996	Arrendale et al.
5,630,835	A	5/1997	Brownlee
5,697,956	A	12/1997	Bornzin
5,703,461	A	12/1997	Minoshima et al.
5,703,573	A	12/1997	Fujimoto et al.
5,710,413	A	1/1998	King et al.
5,742,471	A	4/1998	Barbee, Jr. et al.
5,821,728	A	10/1998	Sshwind
5,821,731	A	10/1998	Kuki et al.
5,864,323	A	1/1999	Berthon
5,898,579	A	4/1999	Boys et al.
5,903,134	A	5/1999	Takeuchi
5,923,544	A	7/1999	Urano
5,940,509	A	8/1999	Jovanovich et al.
5,957,956	A	9/1999	Kroll et al.
5,959,245	A	9/1999	Moe et al.
5,986,895	A	11/1999	Stewart et al.
5,993,996	A	11/1999	Firsich
5,999,308	A	12/1999	Nelson et al.
6,012,659	A	1/2000	Nakazawa et al.
6,047,214	A	4/2000	Mueller et al.
6,066,163	A	5/2000	John
6,067,473	A	5/2000	Greeninger et al.
6,108,579	A	8/2000	Snell et al.
6,127,799	A	10/2000	Krishnan
6,176,433	B1	1/2001	Uesaka et al.
6,184,651	B1	2/2001	Fernandez et al.
6,207,887	B1	3/2001	Bass et al.
6,232,841	B1	5/2001	Bartlett et al.
6,238,387	B1	5/2001	Miller, III
6,252,762	B1	6/2001	Amatucci
6,436,299	B1	8/2002	Baarman et al.
6,450,946	B1	9/2002	Forsell
6,452,465	B1	9/2002	Brown et al.
6,459,218	B2	10/2002	Boys et al.
6,473,028	B1	10/2002	Luc
6,483,202	B1	11/2002	Boys
6,515,878	B1	2/2003	Meins et al.
6,535,133	B2	3/2003	Gohara
6,561,975	B1	5/2003	Pool et al.
6,563,425	B2	5/2003	Nicholson et al.
6,597,076	B2	7/2003	Scheible et al.
6,609,023	B1	8/2003	Fischell et al.
6,631,072	B1	10/2003	Paul et al.
6,650,227	B1	11/2003	Bradin
6,664,770	B1	12/2003	Bartels
6,673,250	B2	1/2004	Kuennen et al.
6,683,256	B2	1/2004	Kao
6,696,647	B2	2/2004	Ono et al.
6,703,921	B1	3/2004	Wuidart et al.
6,731,071	B2	5/2004	Baarman
6,749,119	B2	6/2004	Scheible et al.
6,772,011	B2	8/2004	Dolgin
6,798,716	B1	9/2004	Charych
6,803,744	B1	10/2004	Sabo
6,806,649	B2	10/2004	Mollema et al.
6,812,645	B2	11/2004	Baarman
6,825,620	B2	11/2004	Kuennen et al.
6,831,417	B2	12/2004	Baarman
6,839,035	B1	1/2005	Addonisio et al.
6,844,702	B2	1/2005	Giannopoulos et al.
6,856,291	B2	2/2005	Mickle et al.
6,858,970	B2	2/2005	Malkin et al.
6,906,495	B2	6/2005	Cheng et al.
6,917,163	B2	7/2005	Baarman
6,917,431	B2	7/2005	Soljacic et al.
6,937,130	B2	8/2005	Scheible et al.
6,960,968	B2	11/2005	Odendaal et al.
6,961,619	B2	11/2005	Casey
6,967,462	B1	11/2005	Landis
6,975,198	B2	12/2005	Baarman et al.
6,988,026	B2	1/2006	Breed et al.
7,027,311	B2	4/2006	Vanderelli et al.
7,035,076	B1	4/2006	Stevenson
7,042,196	B2	5/2006	Ka-Lai et al.
7,069,064	B2	6/2006	Gevorgian et al.
7,084,605	B2	8/2006	Mickle et al.
7,116,200	B2	10/2006	Baarman et al.
7,118,240	B2	10/2006	Baarman et al.
7,126,450	B2	10/2006	Baarman et al.
7,127,293	B2	10/2006	MacDonald
7,132,918	B2	11/2006	Baarman et al.
7,147,604	B1	12/2006	Allen et al.
7,180,248	B2	2/2007	Kuennen et al.
7,191,007	B2	3/2007	Desai et al.
7,193,418	B2	3/2007	Freytag
D541,322	S	4/2007	Garrett et al.
7,212,414	B2	5/2007	Baarman
7,233,137	B2	6/2007	Nakamura et al.
D545,855	S	7/2007	Garrett et al.
7,239,110	B2	7/2007	Cheng et al.
7,248,017	B2	7/2007	Cheng et al.
7,251,527	B2	7/2007	Lyden
7,288,918	B2	10/2007	DiStefano
7,340,304	B2	3/2008	MacDonald
7,375,492	B2	5/2008	Calhoon et al.
7,375,493	B2	5/2008	Calhoon et al.
7,378,817	B2	5/2008	Calhoon et al.
7,382,636	B2	6/2008	Baarman et al.
7,385,357	B2	6/2008	Kuennen et al.
7,443,135	B2	10/2008	Cho
7,462,951	B1	12/2008	Baarman
7,466,213	B2	12/2008	Löbl et al.
7,471,062	B2	12/2008	Bruning
7,474,058	B2	1/2009	Baarman
7,492,247	B2	2/2009	Schmidt et al.
7,514,818	B2	4/2009	Abe et al.
7,518,267	B2	4/2009	Baarman
7,521,890	B2	4/2009	Lee et al.
7,525,283	B2	4/2009	Cheng et al.
7,545,337	B2	6/2009	Guenther
7,554,316	B2	6/2009	Stevens et al.
7,599,743	B2	10/2009	Hassler, Jr. et al.
7,615,936	B2	11/2009	Baarman et al.
7,639,514	B2	12/2009	Baarman
7,741,734	B2	6/2010	Joannopoulos et al.
7,795,708	B2	9/2010	Katti
7,825,543	B2	11/2010	Karalis et al.
7,825,544	B2	11/2010	Jansen et al.
7,835,417	B2	11/2010	Heideman et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,843,288	B2	11/2010	Lee et al.
7,844,306	B2	11/2010	Shearer et al.
7,863,859	B2	1/2011	Soar
7,868,588	B2	1/2011	Altekruse et al.
7,879,483	B2	2/2011	Sakakibara
7,880,337	B2	2/2011	Farkas
7,884,697	B2	2/2011	Wei et al.
7,885,050	B2	2/2011	Lee
7,893,564	B2	2/2011	Bennett
7,919,886	B2	4/2011	Tanaka
7,923,870	B2	4/2011	Jin
7,932,798	B2	4/2011	Tolle et al.
7,936,147	B2	5/2011	Kook
7,948,209	B2	5/2011	Jung
7,952,322	B2	5/2011	Partovi et al.
7,963,941	B2	6/2011	Wilk
7,969,045	B2	6/2011	Schmidt et al.
7,994,880	B2	8/2011	Chen et al.
7,999,506	B1	8/2011	Hollar et al.
8,022,576	B2	9/2011	Joannopoulos et al.
8,030,887	B2	10/2011	Jung
8,035,255	B2	10/2011	Kurs et al.
8,076,800	B2	12/2011	Joannopoulos et al.
8,076,801	B2	12/2011	Karalis et al.
8,084,889	B2	12/2011	Joannopoulos et al.
8,097,983	B2	1/2012	Karalis et al.
8,106,539	B2	1/2012	Schatz et al.
8,115,448	B2	2/2012	John
8,131,378	B2	3/2012	Greenberg et al.
8,178,995	B2	5/2012	Amano et al.
8,188,826	B2	5/2012	Okada et al.
8,193,769	B2	6/2012	Azancot et al.
8,212,414	B2	7/2012	Howard et al.
8,241,097	B2	8/2012	Zhu et al.
8,260,200	B2	9/2012	Shimizu et al.
8,269,375	B2	9/2012	Sogabe et al.
8,304,935	B2	11/2012	Karalis et al.
8,310,107	B2	11/2012	Jin
8,314,513	B2	11/2012	Aoyama et al.
8,324,759	B2	12/2012	Karalis et al.
8,334,620	B2	12/2012	Park et al.
8,344,688	B2	1/2013	Yoda et al.
8,362,651	B2	1/2013	Hamam et al.
8,369,905	B2	2/2013	Sogabe et al.
8,395,282	B2	3/2013	Joannopoulos et al.
8,395,283	B2	3/2013	Joannopoulos et al.
8,400,017	B2	3/2013	Kurs et al.
8,400,018	B2	3/2013	Joannopoulos et al.
8,400,019	B2	3/2013	Joannopoulos et al.
8,400,020	B2	3/2013	Joannopoulos et al.
8,400,021	B2	3/2013	Joannopoulos et al.
8,400,022	B2	3/2013	Joannopoulos et al.
8,400,023	B2	3/2013	Joannopoulos et al.
8,400,024	B2	3/2013	Joannopoulos et al.
8,406,823	B2	3/2013	Kondo et al.
8,410,636	B2	4/2013	Kurs et al.
8,441,154	B2	5/2013	Karalis et al.
8,446,046	B2	5/2013	Fells et al.
8,457,547	B2	6/2013	Meskens
8,461,719	B2	6/2013	Kesler et al.
8,461,720	B2	6/2013	Kurs et al.
8,461,721	B2	6/2013	Karalis et al.
8,461,722	B2	6/2013	Kurs et al.
8,461,817	B2	6/2013	Martin et al.
8,466,583	B2	6/2013	Karalis et al.
8,471,410	B2	6/2013	Karalis et al.
8,476,788	B2	7/2013	Karalis et al.
8,482,157	B2	7/2013	Cook et al.
8,482,158	B2	7/2013	Kurs et al.
8,487,480	B1	7/2013	Kesler et al.
8,497,601	B2	7/2013	Hall et al.
8,552,592	B2	10/2013	Schatz et al.
8,569,914	B2	10/2013	Karalis et al.
8,587,153	B2	11/2013	Schatz et al.
8,587,155	B2	11/2013	Giler et al.
8,598,743	B2	12/2013	Hall et al.
8,618,696	B2	12/2013	Karalis et al.
8,629,578	B2	1/2014	Kurs et al.
8,643,326	B2	2/2014	Campanella et al.
2002/0032471	A1	3/2002	Loftin et al.
2002/0056233	A1	5/2002	Gohara
2002/0105343	A1	8/2002	Scheible et al.
2002/0118004	A1	8/2002	Scheible et al.
2002/0130642	A1	9/2002	Ettes et al.
2002/0167294	A1	11/2002	Odaohhara
2003/0038641	A1	2/2003	Scheible
2003/0062794	A1	4/2003	Scheible et al.
2003/0062980	A1	4/2003	Scheible et al.
2003/0071034	A1	4/2003	Thompson et al.
2003/0124050	A1	7/2003	Yadav et al.
2003/0126948	A1	7/2003	Yadav et al.
2003/0160590	A1	8/2003	Schaefer et al.
2003/0199778	A1	10/2003	Mickle et al.
2003/0214255	A1	11/2003	Baarman et al.
2004/0000974	A1	1/2004	Odenaal et al.
2004/0026998	A1	2/2004	Henriott et al.
2004/0100338	A1	5/2004	Clark
2004/0113847	A1	6/2004	Qi et al.
2004/0130425	A1	7/2004	Dayan et al.
2004/0130915	A1	7/2004	Baarman
2004/0130916	A1	7/2004	Baarman
2004/0142733	A1	7/2004	Parise
2004/0150934	A1	8/2004	Baarman
2004/0189246	A1	9/2004	Bulai et al.
2004/0201361	A1	10/2004	Koh et al.
2004/0222751	A1	11/2004	Mollema et al.
2004/0227057	A1	11/2004	Tuominen et al.
2004/0232845	A1	11/2004	Baarman et al.
2004/0233043	A1	11/2004	Yazawa et al.
2004/0267501	A1	12/2004	Freed et al.
2005/0007067	A1	1/2005	Baarman et al.
2005/0021134	A1	1/2005	Opie
2005/0027192	A1	2/2005	Govari et al.
2005/0033382	A1	2/2005	Single
2005/0085873	A1	4/2005	Gord et al.
2005/0093475	A1	5/2005	Kuennen et al.
2005/0104064	A1	5/2005	Hegarty et al.
2005/0104453	A1	5/2005	Vanderelli et al.
2005/0116650	A1	6/2005	Baarman
2005/0116683	A1	6/2005	Cheng et al.
2005/0122058	A1	6/2005	Baarman et al.
2005/0122059	A1	6/2005	Baarman et al.
2005/0125093	A1	6/2005	Kikuchi et al.
2005/0127849	A1	6/2005	Baarman et al.
2005/0127850	A1	6/2005	Baarman et al.
2005/0127866	A1	6/2005	Hamilton et al.
2005/0135122	A1	6/2005	Cheng et al.
2005/0140482	A1	6/2005	Cheng et al.
2005/0151511	A1	7/2005	Chary
2005/0156560	A1	7/2005	Shimaoka et al.
2005/0189945	A1	9/2005	Reiderman
2005/0194926	A1	9/2005	Di Stefano
2005/0253152	A1	11/2005	Klimov et al.
2005/0288739	A1	12/2005	Hassler, Jr. et al.
2005/0288740	A1	12/2005	Hassler, Jr. et al.
2005/0288741	A1	12/2005	Hassler, Jr. et al.
2005/0288742	A1	12/2005	Giordano et al.
2006/0001509	A1	1/2006	Gibbs
2006/0010902	A1	1/2006	Trinh et al.
2006/0022636	A1	2/2006	Xian et al.
2006/0053296	A1	3/2006	Busboom et al.
2006/0061323	A1	3/2006	Cheng et al.
2006/0066443	A1	3/2006	Hall
2006/0090956	A1	5/2006	Peshkovskiy et al.
2006/0132045	A1	6/2006	Baarman
2006/0164866	A1	7/2006	Vanderelli et al.
2006/0181242	A1	8/2006	Freed et al.
2006/0184209	A1	8/2006	John et al.
2006/0184210	A1	8/2006	Singhal et al.
2006/0185809	A1	8/2006	Elfrink et al.
2006/0199620	A1	9/2006	Greene et al.
2006/0202665	A1	9/2006	Hsu
2006/0205381	A1	9/2006	Beart et al.
2006/0214626	A1	9/2006	Nilson et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2006/0219448 A1 10/2006 Grieve et al.
2006/0238365 A1 10/2006 Vecchione et al.
2006/0270440 A1 11/2006 Shearer et al.
2006/0281435 A1 12/2006 Shearer et al.
2007/0010295 A1 1/2007 Greene et al.
2007/0013483 A1 1/2007 Stewart
2007/0016089 A1 1/2007 Fischell et al.
2007/0021140 A1 1/2007 Keyes, IV et al.
2007/0024246 A1 2/2007 Flaugher
2007/0064406 A1 3/2007 Beart
2007/0069687 A1 3/2007 Suzuki
2007/0096875 A1 5/2007 Waterhouse et al.
2007/0105429 A1 5/2007 Kohl et al.
2007/0117596 A1 5/2007 Greene et al.
2007/0126650 A1 6/2007 Guenther
2007/0145830 A1 6/2007 Lee et al.
2007/0164839 A1 7/2007 Naito
2007/0171681 A1 7/2007 Baarman
2007/0176840 A1 8/2007 Pristas et al.
2007/0178945 A1 8/2007 Cook et al.
2007/0182367 A1 8/2007 Partovi
2007/0208263 A1 9/2007 John et al.
2007/0222542 A1 9/2007 Joannopoulos et al.
2007/0228833 A1 10/2007 Stevens et al.
2007/0257636 A1 11/2007 Phillips et al.
2007/0267918 A1 11/2007 Gyland
2007/0276538 A1 11/2007 Kjellsson et al.
2008/0012569 A1 1/2008 Hall et al.
2008/0014897 A1 1/2008 Cook et al.
2008/0030415 A1 2/2008 Homan et al.
2008/0036588 A1 2/2008 Iverson et al.
2008/0047727 A1 2/2008 Sexton et al.
2008/0051854 A1 2/2008 Bulkes et al.
2008/0067874 A1 3/2008 Tseng
2008/0132909 A1 6/2008 Jascob et al.
2008/0154331 A1 6/2008 John et al.
2008/0176521 A1 7/2008 Singh et al.
2008/0191638 A1 8/2008 Kuennen et al.
2008/0197710 A1 8/2008 Kreitz et al.
2008/0197802 A1 8/2008 Onishi et al.
2008/0211320 A1 9/2008 Cook et al.
2008/0238364 A1 10/2008 Weber et al.
2008/0255901 A1 10/2008 Carroll et al.
2008/0265684 A1 10/2008 Farkas
2008/0266748 A1 10/2008 Lee
2008/0272860 A1 11/2008 Pance
2008/0273242 A1 11/2008 Woodgate et al.
2008/0278264 A1 11/2008 Karalis et al.
2008/0290736 A1 11/2008 Onishi et al.
2008/0291277 A1 11/2008 Jacobsen et al.
2008/0300657 A1 12/2008 Stultz
2008/0300660 A1 12/2008 John
2009/0010028 A1 1/2009 Baarman et al.
2009/0015075 A1 1/2009 Cook et al.
2009/0033280 A1 2/2009 Choi et al.
2009/0033564 A1 2/2009 Cook et al.
2009/0038623 A1 2/2009 Farbarik et al.
2009/0045772 A1 2/2009 Cook et al.
2009/0051224 A1 2/2009 Cook et al.
2009/0058189 A1 3/2009 Cook
2009/0058361 A1 3/2009 John
2009/0067198 A1 3/2009 Graham et al.
2009/0072627 A1 3/2009 Cook et al.
2009/0072628 A1 3/2009 Cook et al.
2009/0072629 A1 3/2009 Cook
2009/0072782 A1 3/2009 Randall
2009/0079268 A1 3/2009 Cook et al.
2009/0079387 A1 3/2009 Jin et al.
2009/0085408 A1 4/2009 Bruhn
2009/0085706 A1 4/2009 Baarman et al.
2009/0095449 A1 4/2009 Bandai et al.
2009/0096413 A1 4/2009 Partovi et al.
2009/0102292 A1 4/2009 Cook et al.
2009/0102296 A1 4/2009 Green et al.
2009/0108679 A1 4/2009 Porwal
2009/0108997 A1 4/2009 Petterson et al.
2009/0115628 A1 5/2009 Dicks et al.
2009/0127937 A1 5/2009 Widmer et al.
2009/0134712 A1 5/2009 Cook et al.
2009/0146892 A1 6/2009 Shimizu et al.
2009/0153273 A1 6/2009 Chen et al.
2009/0160261 A1 6/2009 Elo
2009/0161078 A1 6/2009 Wu et al.
2009/0167253 A1 7/2009 Muraoka et al.
2009/0167449 A1 7/2009 Cook et al.
2009/0174263 A1 7/2009 Baarman et al.
2009/0179502 A1 7/2009 Cook et al.
2009/0188396 A1 7/2009 Hofmann et al.
2009/0189458 A1 7/2009 Kawasaki
2009/0195332 A1 8/2009 Joannopoulos et al.
2009/0195333 A1 8/2009 Joannopoulos et al.
2009/0212636 A1 8/2009 Cook et al.
2009/0213028 A1 8/2009 Cook et al.
2009/0218884 A1 9/2009 Soar
2009/0224608 A1 9/2009 Cook et al.
2009/0224609 A1 9/2009 Cook et al.
2009/0224723 A1 9/2009 Tanabe
2009/0224856 A1 9/2009 Karalis et al.
2009/0230777 A1 9/2009 Baarman et al.
2009/0237194 A1 9/2009 Waffenschmidt et al.
2009/0243394 A1 10/2009 Levine
2009/0243397 A1 10/2009 Cook et al.
2009/0251008 A1 10/2009 Sugaya
2009/0261778 A1 10/2009 Kook
2009/0267558 A1 10/2009 Jung
2009/0267709 A1 10/2009 Joannopoulos et al.
2009/0267710 A1 10/2009 Joannopoulos et al.
2009/0271047 A1 10/2009 Wakamatsu
2009/0271048 A1 10/2009 Wakamatsu
2009/0273242 A1 11/2009 Cook
2009/0273318 A1 11/2009 Rondoni et al.
2009/0278523 A1 11/2009 Yoda et al.
2009/0281678 A1 11/2009 Wakamatsu
2009/0284082 A1 11/2009 Mohammadian
2009/0284083 A1 11/2009 Karalis et al.
2009/0284218 A1 11/2009 Mohammadian et al.
2009/0284220 A1 11/2009 Toncich et al.
2009/0284227 A1 11/2009 Mohammadian et al.
2009/0284245 A1 11/2009 Kirby et al.
2009/0284341 A1 11/2009 Okada et al.
2009/0284369 A1 11/2009 Toncich et al.
2009/0286470 A1 11/2009 Mohammadian et al.
2009/0286475 A1 11/2009 Toncich
2009/0286476 A1 11/2009 Toncich et al.
2009/0289595 A1 11/2009 Chen et al.
2009/0299918 A1 12/2009 Cook et al.
2009/0322158 A1 12/2009 Stevens et al.
2009/0322280 A1 12/2009 Kamijo et al.
2010/0015918 A1 1/2010 Liu et al.
2010/0017249 A1 1/2010 Fincham et al.
2010/0033021 A1 2/2010 Bennett
2010/0034238 A1 2/2010 Bennett
2010/0036773 A1 2/2010 Bennett
2010/0038970 A1 2/2010 Cook et al.
2010/0045114 A1 2/2010 Sample et al.
2010/0052431 A1 3/2010 Mita
2010/0052811 A1 3/2010 Smith et al.
2010/0060077 A1 3/2010 Paulus et al.
2010/0065352 A1 3/2010 Ichikawa
2010/0066349 A1 3/2010 Lin et al.
2010/0076524 A1 3/2010 Forsberg et al.
2010/0081379 A1 4/2010 Cooper et al.
2010/0094381 A1 4/2010 Kim et al.
2010/0096934 A1 4/2010 Joannopoulos et al.
2010/0102639 A1 4/2010 Joannopoulos et al.
2010/0102640 A1 4/2010 Joannopoulos et al.
2010/0102641 A1 4/2010 Joannopoulos et al.
2010/0104031 A1 4/2010 Lacour
2010/0109443 A1 5/2010 Cook et al.
2010/0109445 A1 5/2010 Kurs et al.
2010/0109604 A1 5/2010 Boys et al.
2010/0115474 A1 5/2010 Takada et al.
2010/0117454 A1 5/2010 Cook et al.
2010/0117455 A1 5/2010 Joannopoulos et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2010/0117456 A1 5/2010 Karalis et al.
2010/0117596 A1 5/2010 Cook et al.
2010/0123353 A1 5/2010 Joannopoulos et al.
2010/0123354 A1 5/2010 Joannopoulos et al.
2010/0123355 A1 5/2010 Joannopoulos et al.
2010/0123452 A1 5/2010 Amano et al.
2010/0123530 A1 5/2010 Park et al.
2010/0127573 A1 5/2010 Joannopoulos et al.
2010/0127574 A1 5/2010 Joannopoulos et al.
2010/0127575 A1 5/2010 Joannopoulos et al.
2010/0127660 A1 5/2010 Cook et al.
2010/0133918 A1 6/2010 Joannopoulos et al.
2010/0133919 A1 6/2010 Joannopoulos et al.
2010/0133920 A1 6/2010 Joannopoulos et al.
2010/0141042 A1 6/2010 Kesler et al.
2010/0148589 A1 6/2010 Hamam et al.
2010/0148723 A1 6/2010 Cook et al.
2010/0151808 A1 6/2010 Toncich et al.
2010/0156346 A1 6/2010 Takada et al.
2010/0156355 A1 6/2010 Bauerle et al.
2010/0156570 A1 6/2010 Hong et al.
2010/0164295 A1 7/2010 Ichikawa et al.
2010/0164296 A1 7/2010 Kurs
2010/0164297 A1 7/2010 Kurs et al.
2010/0164298 A1 7/2010 Karalis et al.
2010/0171368 A1 7/2010 Schatz et al.
2010/0171370 A1 7/2010 Karalis et al.
2010/0179384 A1 7/2010 Hoeg et al.
2010/0181843 A1 7/2010 Schatz et al.
2010/0181844 A1 7/2010 Karalis et al.
2010/0181845 A1 7/2010 Fiorello et al.
2010/0181961 A1 7/2010 Novak et al.
2010/0181964 A1 7/2010 Huggins et al.
2010/0184371 A1 7/2010 Cook et al.
2010/0187911 A1 7/2010 Joannopoulos et al.
2010/0187913 A1 7/2010 Smith et al.
2010/0188183 A1 7/2010 Shpiro
2010/0190435 A1 7/2010 Cook et al.
2010/0190436 A1 7/2010 Cook et al.
2010/0194206 A1 8/2010 Burdo et al.
2010/0194207 A1 8/2010 Graham
2010/0194334 A1 8/2010 Kirby et al.
2010/0194335 A1 8/2010 Kirby et al.
2010/0201189 A1 8/2010 Kirby et al.
2010/0201201 A1 8/2010 Mobarhan et al.
2010/0201202 A1 8/2010 Kirby et al.
2010/0201203 A1 8/2010 Schatz et al.
2010/0201204 A1 8/2010 Sakoda et al.
2010/0201205 A1 8/2010 Karalis et al.
2010/0201310 A1 8/2010 Vorenkamp et al.
2010/0201312 A1 8/2010 Kirby et al.
2010/0201313 A1 8/2010 Vorenkamp et al.
2010/0201316 A1 8/2010 Takada et al.
2010/0201513 A1 8/2010 Vorenkamp et al.
2010/0207458 A1 8/2010 Joannopoulos et al.
2010/0210233 A1 8/2010 Cook et al.
2010/0213770 A1 8/2010 Kikuchi
2010/0213895 A1 8/2010 Keating et al.
2010/0217553 A1 8/2010 Von Novak et al.
2010/0219694 A1 9/2010 Kurs et al.
2010/0219695 A1 9/2010 Komiyama et al.
2010/0219696 A1 9/2010 Kojima
2010/0222010 A1 9/2010 Ozaki et al.
2010/0225175 A1 9/2010 Karalis et al.
2010/0225270 A1 9/2010 Jacobs et al.
2010/0225271 A1 9/2010 Oyobe et al.
2010/0225272 A1 9/2010 Kirby et al.
2010/0231053 A1 9/2010 Karalis et al.
2010/0231163 A1 9/2010 Mashinsky
2010/0231340 A1 9/2010 Fiorello et al.
2010/0234922 A1 9/2010 Forsell
2010/0235006 A1 9/2010 Brown
2010/0237706 A1 9/2010 Karalis et al.
2010/0237707 A1 9/2010 Karalis et al.
2010/0237708 A1 9/2010 Karalis et al.
2010/0237709 A1 9/2010 Hall et al.
2010/0244576 A1 9/2010 Hillan et al.
2010/0244577 A1 9/2010 Shimokawa
2010/0244578 A1 9/2010 Yoshikawa
2010/0244579 A1 9/2010 Sogabe et al.
2010/0244580 A1 9/2010 Uchida et al.
2010/0244581 A1 9/2010 Uchida
2010/0244582 A1 9/2010 Yoshikawa
2010/0244583 A1 9/2010 Shimokawa
2010/0244767 A1 9/2010 Turner et al.
2010/0244839 A1 9/2010 Yoshikawa
2010/0248622 A1 9/2010 Lyell Kirby et al.
2010/0253152 A1 10/2010 Karalis et al.
2010/0253281 A1 10/2010 Li
2010/0256481 A1 10/2010 Mareci et al.
2010/0256831 A1 10/2010 Abramo et al.
2010/0259108 A1 10/2010 Giler et al.
2010/0259109 A1 10/2010 Sato
2010/0259110 A1 10/2010 Kurs et al.
2010/0264745 A1 10/2010 Karalis et al.
2010/0264746 A1 10/2010 Kazama et al.
2010/0264747 A1 10/2010 Hall et al.
2010/0276995 A1 11/2010 Marzetta et al.
2010/0277003 A1 11/2010 Von Novak et al.
2010/0277004 A1 11/2010 Suzuki et al.
2010/0277005 A1 11/2010 Karalis et al.
2010/0277120 A1 11/2010 Cook et al.
2010/0277121 A1 11/2010 Hall et al.
2010/0289341 A1 11/2010 Ozaki et al.
2010/0289449 A1 11/2010 Elo
2010/0295505 A1 11/2010 Jung et al.
2010/0295506 A1 11/2010 Ichikawa
2010/0308939 A1 12/2010 Kurs
2010/0314946 A1 12/2010 Budde et al.
2010/0327660 A1 12/2010 Karalis et al.
2010/0327661 A1 12/2010 Karalis et al.
2010/0328044 A1 12/2010 Waffenschmidt et al.
2011/0004269 A1 1/2011 Strother et al.
2011/0012431 A1 1/2011 Karalis et al.
2011/0018361 A1 1/2011 Karalis et al.
2011/0025131 A1 2/2011 Karalis et al.
2011/0025265 A1 2/2011 Mochida et al.
2011/0031928 A1 2/2011 Soar
2011/0043046 A1 2/2011 Joannopoulos et al.
2011/0043047 A1 2/2011 Karalis et al.
2011/0043048 A1 2/2011 Karalis et al.
2011/0043049 A1 2/2011 Karalis et al.
2011/0049995 A1 3/2011 Hashiguchi
2011/0049996 A1 3/2011 Karalis et al.
2011/0049998 A1 3/2011 Karalis et al.
2011/0074218 A1 3/2011 Karalis et al.
2011/0074346 A1 3/2011 Hall et al.
2011/0074347 A1 3/2011 Karalis et al.
2011/0089895 A1 4/2011 Karalis et al.
2011/0095618 A1 4/2011 Schatz et al.
2011/0115303 A1 5/2011 Baarman et al.
2011/0115431 A1 5/2011 Dunworth et al.
2011/0121920 A1 5/2011 Kurs et al.
2011/0128015 A1 6/2011 Dorairaj et al.
2011/0140544 A1 6/2011 Karalis et al.
2011/0148219 A1 6/2011 Karalis et al.
2011/0162895 A1 7/2011 Karalis et al.
2011/0169339 A1 7/2011 Karalis et al.
2011/0181122 A1 7/2011 Karalis et al.
2011/0193416 A1 8/2011 Campanella et al.
2011/0193419 A1 8/2011 Karalis et al.
2011/0198939 A1 8/2011 Karalis et al.
2011/0215086 A1 9/2011 Yeh
2011/0221278 A1 9/2011 Karalis et al.
2011/0227528 A1 9/2011 Karalis et al.
2011/0227530 A1 9/2011 Karalis et al.
2011/0241618 A1 10/2011 Karalis et al.
2011/0248573 A1 10/2011 Kanno et al.
2011/0254377 A1 10/2011 Wildmer et al.
2011/0254503 A1 10/2011 Widmer et al.
2011/0266878 A9 11/2011 Cook et al.
2011/0278943 A1 11/2011 Eckhoff et al.
2011/0318618 A1 12/2011 Yajima et al.
2012/0001492 A9 1/2012 Cook et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2012/0001593	A1	1/2012	DiGuardo	
2012/0007435	A1	1/2012	Sada et al.	
2012/0007441	A1	1/2012	John et al.	
2012/0025602	A1	2/2012	Boys et al.	
2012/0032522	A1	2/2012	Schatz et al.	
2012/0038525	A1	2/2012	Monsalve Carcelen et al.	
2012/0049650	A1	3/2012	Bella	
2012/0062345	A1	3/2012	Kurs et al.	
2012/0068549	A1	3/2012	Karalis et al.	
2012/0086284	A1	4/2012	Capanella et al.	
2012/0086867	A1	4/2012	Kesler et al.	
2012/0091794	A1	4/2012	Campanella et al.	
2012/0091795	A1	4/2012	Fiorello et al.	
2012/0091796	A1	4/2012	Kesler et al.	
2012/0091797	A1	4/2012	Kesler et al.	
2012/0091819	A1	4/2012	Kulikowski et al.	
2012/0091820	A1	4/2012	Campanella et al.	
2012/0091949	A1	4/2012	Campanella et al.	
2012/0091950	A1	4/2012	Campanella et al.	
2012/0098350	A1	4/2012	Campanella et al.	
2012/0112531	A1	5/2012	Kesler et al.	
2012/0112532	A1	5/2012	Kesler et al.	
2012/0112534	A1	5/2012	Kesler et al.	
2012/0112535	A1	5/2012	Karalis et al.	
2012/0112536	A1	5/2012	Karalis et al.	
2012/0112538	A1	5/2012	Kesler et al.	
2012/0112691	A1	5/2012	Kurs et al.	
2012/0119569	A1	5/2012	Karalis et al.	
2012/0119575	A1	5/2012	Kurs et al.	
2012/0119576	A1	5/2012	Kesler et al.	
2012/0119698	A1	5/2012	Karalis et al.	
2012/0139355	A1	6/2012	Ganem et al.	
2012/0146575	A1	6/2012	Armstrong et al.	
2012/0146580	A1*	6/2012	Kitamura	320/108
2012/0153732	A1	6/2012	Kurs et al.	
2012/0153733	A1	6/2012	Schatz et al.	
2012/0153734	A1	6/2012	Kurs et al.	
2012/0153735	A1	6/2012	Karalis et al.	
2012/0153736	A1	6/2012	Karalis et al.	
2012/0153737	A1	6/2012	Karalis et al.	
2012/0153738	A1	6/2012	Karalis et al.	
2012/0153893	A1	6/2012	Schatz et al.	
2012/0175967	A1	7/2012	Dibben et al.	
2012/0181875	A1	7/2012	Wechlin et al.	
2012/0184338	A1	7/2012	Kesler et al.	
2012/0187757	A1	7/2012	Wechlin et al.	
2012/0206096	A1	8/2012	John	
2012/0223573	A1	9/2012	Schatz et al.	
2012/0228952	A1	9/2012	Hall et al.	
2012/0228953	A1	9/2012	Kesler et al.	
2012/0228954	A1	9/2012	Kesler et al.	
2012/0235500	A1	9/2012	Ganem et al.	
2012/0235501	A1	9/2012	Kesler et al.	
2012/0235502	A1	9/2012	Kesler et al.	
2012/0235503	A1	9/2012	Kesler et al.	
2012/0235504	A1	9/2012	Kesler et al.	
2012/0235505	A1	9/2012	Schatz et al.	
2012/0235566	A1	9/2012	Karalis et al.	
2012/0235567	A1	9/2012	Karalis et al.	
2012/0235633	A1	9/2012	Kesler et al.	
2012/0235634	A1	9/2012	Hall et al.	
2012/0239117	A1	9/2012	Kesler et al.	
2012/0242159	A1	9/2012	Lou et al.	
2012/0242225	A1	9/2012	Karalis et al.	
2012/0248884	A1	10/2012	Karalis et al.	
2012/0248886	A1	10/2012	Kesler et al.	
2012/0248887	A1	10/2012	Kesler et al.	
2012/0248888	A1	10/2012	Kesler et al.	
2012/0248981	A1	10/2012	Karalis et al.	
2012/0256494	A1	10/2012	Kesler et al.	
2012/0267960	A1	10/2012	Low et al.	
2012/0280765	A1	11/2012	Kurs et al.	
2012/0313449	A1	12/2012	Kurs et al.	
2012/0313742	A1	12/2012	Kurs et al.	
2013/0007949	A1	1/2013	Kurs et al.	
2013/0020878	A1	1/2013	Karalis et al.	
2013/0033118	A1	2/2013	Karalis et al.	
2013/0038402	A1	2/2013	Karalis et al.	
2013/0057364	A1	3/2013	Kesler et al.	
2013/0062966	A1	3/2013	Verghese et al.	
2013/0063085	A1	3/2013	Takada et al.	
2013/0069441	A1	3/2013	Verghese et al.	
2013/0069753	A1	3/2013	Kurs et al.	
2013/0099587	A1	4/2013	Lou et al.	
2013/0154383	A1	6/2013	Kasturi et al.	
2013/0154389	A1	6/2013	Kurs et al.	
2013/0159956	A1	6/2013	Verghese et al.	
2013/0175874	A1	7/2013	Lou et al.	
2013/0175875	A1	7/2013	Kurs et al.	
2013/0200716	A1	8/2013	Kesler et al.	
2013/0200721	A1	8/2013	Kurs et al.	
2013/0221744	A1	8/2013	Hall et al.	
2013/0278073	A1	10/2013	Kurs et al.	
2013/0278074	A1	10/2013	Kurs et al.	
2013/0278075	A1	10/2013	Kurs et al.	
2013/0300353	A1	11/2013	Kurs et al.	
2013/0307349	A1	11/2013	Hall et al.	
2013/0320773	A1	12/2013	Schatz et al.	
2013/0334892	A1	12/2013	Hall et al.	
2014/0002012	A1	1/2014	McCauley et al.	
2014/0049422	A1	2/2014	von Novak et al.	
2014/0070764	A1	3/2014	Keeling	

FOREIGN PATENT DOCUMENTS

CN	101983466	3/2011	
CN	102239633	11/2011	
CN	102439669	5/2012	
CN	103329397	9/2013	
DE	3824972 A1	1/1989	
DE	10029147 A1	12/2001	
DE	20016655 U1	2/2002	
DE	10221484 A1	11/2003	
DE	10304584 A1	8/2004	
DE	102005036290 A1	2/2007	
DE	102006044057 A1	4/2008	
DE	20 2009 009693	11/2010	..... H02J 17/00
DE	10 2009 033 236	1/2011	
DE	10 2009 033 237	1/2011	
DE	10 2011 015980	10/2012	
EP	1335477 A2	8/2003	
EP	1 521 206	4/2005	
EP	1 524 010	4/2005	
EP	2340611 A1	7/2011	
EP	2357716 A2	8/2011	
EP	2396796 A1	12/2011	
EP	2 410 631	1/2012	
FR	2 968 616	6/2012	
IN	1734/KOLNP/2011	9/2011	
JP	02097005 A	4/1990	
JP	04265875 A	9/1992	
JP	H6-2975	1/1994	
JP	6-341410	12/1994	
JP	H07-225251	8/1995	
JP	9-182323	7/1997	
JP	09298847 A	11/1997	
JP	10164837 A	6/1998	
JP	11075329 A	3/1999	
JP	11188113 A	7/1999	
JP	2000-134830	5/2000	
JP	2001309580 A	11/2001	
JP	2002010535 A	1/2002	
JP	2003179526 A	6/2003	
JP	2004166459 A	6/2004	
JP	2004201458 A	7/2004	
JP	2004-229144	8/2004	
JP	2005057444 A	3/2005	
JP	2005149238 A	6/2005	
JP	2006-074848	3/2006	
JP	2007505480 A	3/2007	
JP	2007-266892	10/2007	
JP	2007537637 A	12/2007	
JP	2008-17562	1/2008	
JP	2008508842 A	3/2008	

(56) **References Cited**

FOREIGN PATENT DOCUMENTS

JP	2008206231	A	9/2008
JP	2008206327	A	9/2008
JP	2008-295231		12/2008
JP	2009-213295		9/2009
JP	2009-273260		11/2009
JP	2011072074	A *	4/2011
JP	2012504387	A	2/2012
JP	2013-543718		12/2013
KR	10-2007-0017804		2/2007
KR	1020080007635	A	1/2008
KR	1020090122072	A	11/2009
KR	1020110050920	A	5/2011
SG	112842		7/2005
WO	WO-9217929	A1	10/1992
WO	WO-9323908	A1	11/1993
WO	WO-9428560	A1	12/1994
WO	WO 95/11545		4/1995
WO	WO-9602970	A1	2/1996
WO	WO-9850993	A1	11/1998
WO	WO 00/23823		4/2000
WO	WO-0077910	A1	12/2000
WO	WO-03092329	A1	11/2003
WO	WO-03096361	A1	11/2003
WO	WO-03096512	A2	11/2003
WO	WO 2004/015885		2/2004
WO	WO-2004038888	A2	5/2004
WO	WO-2004055654	A2	7/2004
WO	WO-2004073150	A1	8/2004
WO	WO-2004073166	A2	8/2004
WO	WO-2004073176	A2	8/2004
WO	WO-2004073177	A2	8/2004
WO	WO-2004112216	A1	12/2004
WO	WO-2005024865	A2	3/2005
WO	WO-2005060068	A1	6/2005
WO	WO-2005109597	A1	11/2005
WO	WO-2005109598	A1	11/2005
WO	WO-2006011769	A1	2/2006
WO	WO-2007008646	A2	1/2007
WO	WO-2007020583	A2	2/2007
WO	WO-2007042952	A1	4/2007
WO	WO-2007084716	A2	7/2007
WO	WO-2007084717	A2	7/2007
WO	WO-2008109489	A2	9/2008
WO	WO-2008118178	A1	10/2008
WO	WO-2009009559	A1	1/2009
WO	WO-2009018568	A2	2/2009
WO	WO-2009023155	A2	2/2009
WO	WO-2009023646	A2	2/2009
WO	WO-2009033043	A2	3/2009
WO	2009062438	A1	5/2009
WO	WO-2009070730	A2	6/2009
WO	WO 2009/081115		7/2009
WO	WO-2009126963	A2	10/2009
WO	WO-2009140506	A1	11/2009
WO	WO-2009149464	A2	12/2009
WO	WO-2009155000	A2	12/2009
WO	WO-2010030977	A2	3/2010
WO	WO-2010036980	A1	4/2010
WO	WO-2010039967	A1	4/2010
WO	WO-2010090538	A1	8/2010
WO	WO-2010090539	A1	8/2010
WO	WO-2010093997	A1	8/2010
WO	2010104569	A1	9/2010
WO	WO 2010/106648		9/2010
WO	WO 2010/136927		12/2010
WO	2011061388	A1	5/2011
WO	2011061821	A1	5/2011
WO	WO-2011062827	A2	5/2011
WO	WO-2011112795	A1	9/2011
WO	WO-2012037279	A1	3/2012
WO	2012170278	A2	12/2012
WO	2012170278	A3	1/2013
WO	2013013235	A2	1/2013
WO	2013020138	A2	2/2013
WO	2013036947	A2	3/2013
WO	2013020138	A3	4/2013
WO	2013059441	A1	4/2013
WO	2013013235	A3	5/2013
WO	2013036947	A3	5/2013
WO	2013067484	A1	5/2013
WO	WO 2013/113017		8/2013
WO	WO 2013/142840		9/2013
WO	WO 2014/004843		1/2014

OTHER PUBLICATIONS

EPO Communication for European Application No. 12 830 255.1 dated Apr. 28, 2015 (6 pages).

"Next Little Thing 2010 Electricity without wires", CNN Money (See money.cnn.com/galleries/2009/smallbusiness/0911/gallery.next_little_thing_2010.smb/) (dated Nov. 30, 2009).

Ahmadian, M. et al., "Miniature Transmitter for Implantable Micro Systems", *Proceedings of the 25th Annual International Conference of the IEEE EMBS* Cancun, Mexico, pp. 3028-3031 (Sep. 17-21, 2003).

Borenstein, S., "Man tries wirelessly boosting batteries", (The Associated Press), USA Today, (Nov. 16, 2006) 1 page.

Budhia, M. et al., "A New IPT Magnetic Coupler for Electric Vehicle Charging Systems", IECON 2010—36th Annual Conference on IEEE Industrial Electronics Society, Glendale, AZ, pp. 2487-2492 (Nov. 7-10, 2010).

Budhia, M. et al., "Development and evaluation of single sided flux couplers for contactless electric vehicle charging", 2011 IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, pp. 614-621 (Sep. 17-22, 2011).

Budhia, M. et al.,"Development of a Single-Sided Flux Magnetic Coupler for Electric Vehicle IPT", *IEEE Transactions on Industrial Electronics*, vol. 60:318-328 (Jan. 2013).

Eisenberg, Anne, "Automatic Recharging, From a Distance", The New York Times, (see www.nytimes.com/2012/03/11/business/built-in-wireless-chargeing-for-electronic-devices.html?_r=0) (published on Mar. 10, 2012).

Fan, Shanhui et al., "Rate-Equation Analysis of Output Efficiency and Modulation Rate of Photomic-Crystal Light-Emitting Diodes", IEEE Journal of Quantum Electronics, vol. 36(10):1123-1130 (Oct. 2000).

Ferris, David, "How Wireless Charging Will Make Life Simpler (and Greener)", Forbes (See forbes.com/sites/davidferris/2012/07/24/how-wireless-charging-will-make-life-simpler-and-greener/print/) (dated Jul. 24, 2012).

Finkenzeller, Klaus, "RFID Handbook—Fundamentals and Applications in Contactless Smart Cards", Nikkan Kohgyo-sya, Kanno Taihei, first version, pp. 32-37, 253 (Aug. 21, 2001).

Finkenzeller, Klaus, "RFID Handbook (2nd Edition)", The Nikkan Kogyo Shimbun, Ltd., pp. 19, 20, 38, 39, 43, 44, 62, 63, 67, 68, 87, 88, 291, 292 (Published on May 31, 2004).

Ho, S. L. et al., "A Comparative Study Between Novel Witricity and Traditional Inductive Magnetic Coupling in Wireless Charging", IEEE Transactions on Magnetics, vol. 47(5):1522-1525 (May 2011).

Moskvitch, Katia, "Wireless charging—the future for electric cars?", BBC News Technology (See www.bbc.co.uk/news/technology-14183409) (dated Jul. 21, 2011).

Schneider, D. "A Critical Look at Wireless Power", *IEEE Spectrum*, pp. 35-39 (May 2010).

Stewart, W., "The Power to Set you Free", Science, vol. 317:55-56 (Jul. 6, 2007).

Tang, S.C. et al., "Evaluation of the Shielding Effects on Printed-Circuit-Board Transformers Using Ferrite Plates and Copper Sheets", *IEEE Transactions on Power Electronics*, vol. 17:1080-1088 (Nov. 2002).

Villeneuve, Pierre R. et al., "Microcavities in photonic crystals: Mode symmetry, tunability, and coupling efficiency", *Physical Review B*, vol. 54:7837-7842 (Sep. 15, 1996).

Yates, David C. et al., "Optimal Transmission Frequency for Ultralow-Power Short-Range Radio Links", IEEE Transactions on Circuits and Systems—1, Regular Papers, vol. 51:1405-1413 (Jul. 2004).

(56) **References Cited**

OTHER PUBLICATIONS

Ziaie, Babak et al., "A Low-Power Miniature Transmitter Using a Low-Loss Silicon Platform for Biotelemetry", *Proceedings—19th International Conference IEEE/EMBS*, pp. 2221-2224, (Oct. 30-Nov. 2, 1997) 4 pages.
PCT/US2012/054490, International Application Serial No. PCT/US2012/054490, International Preliminary Report on Patentability and Written Opinion mailed Mar. 20, 2014, 9 pages.
PCT/US2011/054544, International Preliminary Report on Patentability for PCT/US2011/054544, mailed on Apr. 18, 2013, 13 pages.
Amrany, Adi, Final Office Action, U.S. Appl. No. 12/899,281, mailed on Jun. 24, 2014 (14 pages).
Amrany, Adi, Final Office Action, U.S. Appl. No. 12/899,281, mailed on Dec. 6, 2013 (8 pages).
Amrany, Adi, Final Office Action, U.S. Appl. No. 12/899,281, mailed on Sep. 6, 2013, 12 pages.
Amrany, Adi, Non-Final Office Action, U.S. Appl. No. 12/899,281, mailed on May 23, 2013 (11 pages).
Amrany, Adi, Restriction Requirement, U.S. Appl. No. 12/899,281, mailed on Mar. 21, 2013 (7 pages).
Fish & Richardson, Reply to Action of Dec. 6, 2013, U.S. Appl. No. 12/899,281, filed May 6, 2014, 15 pages.
Fenwick & West LLP, Amendment B under 37 C.F.R. § 1.116, U.S. Appl. No. 12/899,281, filed Nov. 26, 2013, 11 pages.
Fenwick & West LLP, Response and Amendment A Under 37 C.F.R. § 1.111, U.S. Appl. No. 12/899,281, filed Aug. 23, 2013, 16 pages.
Fenwick & West LLP, Response to Restriction Requirement, U.S. Appl. No. 12/899,281, filed Apr. 19, 2013, 14 pages.
Extended European Search Report for 11184066.6 mailed Mar. 28, 2013, Massachusetts Institute of Technology, 7 pages.
U.S. Appl. No. 12/759,047, Non Final Office Action mailed on Jul. 18, 2013, 7 pages.
Jackson, J. D. , "Classical Electrodynamics", 3rd Edition, Wiley, New York, Sections 1.11, 5.5, 5.17, 6.9, 8.1, 8.8, 9.2, and 9.3, 1999, pp. 40-43, 181-184, 215-218, 264-267, 352-356, 371-374, 410-416.
International Application Serial No. PCT/US2011/051634, International Preliminary Report on Patentability mailed Mar. 28, 2013, Witricity Corporation et al, 8 pages.
International Application Serial No. PCT/US2012/040184, International Search Report and Written Opinion mailed Nov. 28, 2012, Witricity Corporation, 8 pages.
International Application Serial No. PCT/US2012/047844, International Search Report and Written Opinion mailed Mar. 25, 2013, Witricity Corporation et al, 9 pages.
International Application Serial No. PCT/US2012/049777, International Search Report and Written Opinion mailed Jan. 23, 2013, 10 pages.
International Application Serial No. PCT/US2012/054490, International Search Report and Written Opinion mailed Feb. 28, 2013, Witricity Corporation, 8 pages.
International Application Serial No. PCT/US2012/060793, International Search Report and Written Opinion mailed Mar. 8, 2013, Witricity Corporation, 13 pages.
International Application Serial No. PCT/US2012/063530, International Search Report and Written Opinion mailed Mar. 13, 2013, Witricity Corporation, 16 pages.
International Application Serial No. PCT/US2013/023478, International Search Report and Written Opinion mailed Jun. 25, 2013, Witricity Corporation, 15 pages.
Abe et al., "A noncontact Charger Using a Resonant Converter with Parallel Capacitor of the Secondary Coil", IEEE, vol. 36, No. 2, Mar./Apr. 2000, pp. 444-451.
Altchev et al., "Efficient Resonant Inductive Coupling Energy Transfer Using New Magnetic and Design Criteria", IEEE, Jun. 16, 2005, pp. 1293-1298.
Aoki et al., "Observation of strong coupling between one atom and a monolithic microresonator," Nature, vol. 443, Oct. 12, 2006, pp. 671-674.
Apneseth et al., "Introducing wireless proximity switches", ABB Review, Apr. 2002, pp. 42-49.
U.S. Appl. No. 12/613,686, Notice of Allowance mailed Jan. 6, 2011, 10 pages.
U.S. Appl. No. 12/613,686, Notice of Allowance mailed Mar. 7, 2011, 27 pages.
Australian Application Serial No. 2006269374, Examination Report mailed Sep. 18, 2008.
Baker et al., "Feedback Analysis and Design of RF Power Links for Low-Power Bionic Systems", IEEE Transactions on Biomedical Circuits and Systems, vol. 1, No. 1, Mar. 2007, pp. 28-38.
Balanis, Constantine A., Antenna Theory: Analysis and Design, 3rd Edition, Sections 4.2, 4.3, 5.2, 5.3, John Wiley & Sons Inc., 2005, 40 pages.
Berardelli, Phil, "Outlets Are Out", ScienceNOW Daily News, Science Now, http://sciencenow.sciencemag.org/cgi/content/full/2006/1114/2, Nov. 14, 2006, 2 pages.
Biever, Celeste, "Evanescent coupling could power gadgets wirelessly", NewScientistsTech.com, http://www.newscientisttech.com/article.ns?id=dn10575&print=true, Nov. 15, 2006, 2 pages.
Borenstein, Seth, (AP Science writer) "Man tries wirelessly boosting batteries", Boston.com, http://www.boston.com/business/technology/articles/2006/11/15/man_tries_wirelessly_b . . . Nov. 15, 2006, 1 page.
Boyle, Alan, "Electro-nirvana? Not so fast", MSNBC, http://cosmiclog.msnbc.msn.com/_news/2007/06/08/4350760-electro-nirvana-not-so-fast, Jun. 8, 2007, 1 page.
Bulkeley, William M., "MIT Scientists Pave the Way for Wireless Battery Charging", The Wall Street Journal, http://online.wsj.com/article/SB118123955549228045.html?mod=googlenews_wsj, Jun. 8, 2007, 2 pages.
Burri et al., Invention Description, Feb. 5, 2008, 16 pages.
Cass, Stephen, "Air Power—Wireless data connections are common—now scientists are working on wireless power", Sponsored by IEEE Spectrum, http://spectrum.ieee.org/computing/hardware/air-power, Nov. 2006, 2 pages.
Castelvecchi, Davide, "The Power of Induction—Cutting the last cord could resonate with our increasingly gadget-dependent lives", Science News Online, vol. 172, No. 3, Jul. 21, 2007, 6 pages.
Chang, Angela, "Recharging, The Wireless Way—Even physicists forget to recharge their cell phones sometimes", PC Magazine, ABC News Internet Ventures, Dec. 12, 2006, 1 page.
Chinaview, "Scientists light bulb with 'wireless electricity'", www.Chinaview.cn, http://news.xinhuanet.com/english/2007-06/08/content_6215681.htm, Jun. 2007, 1 page.
Cooks, Gareth (Globe staff), "The vision of an MIT physicist: Getting rid of pesky rechargers" Boston.com, Dec. 11, 2006, 1 page.
Derbyshire, David, "The end of the plug? Scientists invent wireless device that beams electricity through your home", Daily Mail, http://www.dailymail.co.uk/pages/live/articles/technology/technology.html?in_article_id=4 . . . , Jun. 7, 2007, 3 pages.
Esser et al., "A New Approach to Power Supplies for Robots", IEEE, vol. 27, No. 5, Sep./Oct. 1991, pp. 872-875.
European Application No. 06 786 588.1-1242, Examination Report mailed Jan. 15, 2009, 5 pages.
Fenske et al., "Dielectric Materials at Microwave Frequencies", Appiied Microwave & Wireless, 2000, pp. 92-100.
Fernandez et al., "A simple DC-DC converter for the power supply of a cochlear implant", Power Electronics Specialist Conference, IEEE 34th Annual, Jun. 2003, pp. 1965-1970.
Fildes, Jonathan, "The technology with impact 2007", BBC News, Dec. 27, 2007, 3 pages.
Fildes, Jonathan, "Wireless energy promise powers up" Science and Technology Report, BBC News, http://news.bbc.co.uk/2/hi/technology/6725955.stm, Jun. 7, 2007, 3 pages.
Fildes, Jonathan, (Science and Technology Reporter), "Physics Promises Wireless Power" BBC News, Nov. 15, 2006, 3 pages.
Freedman, David H., "Power on a Chip", MIT Technology Review, Nov. 2004, 3 pages.
Geyi, Wen, "A Method for the Evaluation of Small Antenna Q, IEEE Transactions on Antennas and Propagation", vol. 51, No. 8, Aug. 2003, pp. 2124-2129.
Hadley, Franklin, "Goodbye Wires—MIT Team Experimentally Demonstrates Wireless Power Transfer, Potentially Useful for Power Laptops, Cell-Phones Without Cords", Massachusetts Insti-

(56) **References Cited**

OTHER PUBLICATIONS

tute of Technology, Institute for Soldier Nanotechnologies, http://web.mit.edu/newsoffice/2007/wireless-0607.html, Jun. 7, 2007, 3 pages.
Haus, H.A., "Waves and Fields in Optoelectronics", Chapter 7 Coupling of Modes—Reasonators and Couplers, 1984, pp. 197-234.
Heikkinen et al., "Performance and Efficiency of Planar Rectennas for Short-Range Wireless Power Transfer at 2.45 GHz", Microwave and Optical Technology Letters, vol. 31, No. 2, Oct. 20, 2001, pp. 86-91.
Highfield, Roger, (Science Editor), "Wireless revolution could spell end of plugs", Telegraph.co.uk, http://www.telegraph.co.uk/news/main.jhtml?xml=/news/2007/06/07/nwireless107.xml, Jun. 7, 2007, 3 pages.
Hirai et al., "Integral Motor with Driver and Wireless Transmission of Power and Information for Autonomous Subspindle Drive", IEEE, vol. 15, No. 1, Jan. 2000, pp. 13-20.
Hirai et al., "Practical Study on Wireless Transmission of Power and Information for Autonomous Decentralized Manufacturing System", IEEE, vol. 46, No. 2, Apr. 1999, pp. 349-359.
Hirai et al., "Study on Intelligent Battery Charging Using Inductive Transmission of Power and Information", IEEE, vol. 15, No. 2, Mar. 2000, pp. 335-345.
Hirai et al., "Wireless Transmission of Power and Information and Information for Cableless Linear Motor Drive", IEEE, vol. 15, No. 1, Jan. 2000, pp. 21-27.
Hirayama, Makoto, "Splashpower—World Leaders in Wireless Power", PowerPoint presentation, Splashpower Japan, Sep. 3, 2007, 30 pages.
In pictures: A year in technology, BBC News, http://news.bbc.co.uk/2/hi/in_pictures/7129507.stm, Dec. 28, 2007, 2 pages.
Infotech Online, "Recharging gadgets without cables", infotech.indiatimes.com, Nov. 17, 2006, 1 page.
Intel News Release, "Intel CTO Says Gap between Humans, Machines Will Close by 2050", (intel.com/.../20080821comp.htm?iid=S . . .), Printed Nov. 6, 2009, 2 pages.
International Application Serial No. PCT/US2006/026480, International Preliminary Report on Patentability mailed Jan. 29, 2008, 8 pages.
International Application Serial No. PCT/US2006/026480, International Search Report and Written Opinion mailed Dec. 21, 2007, 14 pages.
International Application Serial No. PCT/US2007/070892, International Preliminary Report on Patentability mailed Sep. 29, 2009, 14 pages.
International Application Serial No. PCT/US2007/070892, International Search Report and Written Opinion mailed Mar. 3, 2008, 21 pages.
International Application Serial No. PCT/US2009/058499, International Preliminary Report on Patentability mailed Mar. 29, 2011, 5 pages.
International Application Serial No. PCT/US2009/058499, International Search Report and Written Opinion mailed Dec. 10, 2009, 6 pages.
International Application Serial No. PCT/US2009/059244, International Search Report and Written Opinion mailed Dec. 7, 2009, 12 pages.
International Application Serial No. PCT/US2009/43970, International Search Report and Written Opinion mailed Jul. 14, 2009, 9 pages.
International Application Serial No. PCT/US2010/024199, International Preliminary Report on Patentability mailed Aug. 25, 2011, 7 pages.
International Application Serial No. PCT/US2010/024199, International Search Report and Written Opinion mailed May 14, 2010, 12 pages.
International Application Serial No. PCT/US2011/027868, International Preliminary Report on Patentability mailed Sep. 20, 2012, 8 pages.
International Application Serial No. PCT/US2011/027868, International Search Report and Written Opinion mailed Jul. 5, 2011, 9 pages.
International Application Serial No. PCT/US2011/051634, International Search Report and Written Opinion mailed Jan. 6, 2012, 11 pages.
International Application Serial No. PCT/US2011/054544, International Search Report and Written Opinion mailed Jan. 30, 2012, 17 pages.
Jackson, J.D., Classical Electrodynamics, 3rd Edition, 1999, pp. 201-203.
Jacob et al., "Lithium Tantalate—A High Permittivity Dielectric Material for Microwave Communication Systems", Proceedings of IEEE TENCON—Poster Papers, 2003, pp. 1362-1366.
Karalis et al., Efficient Wireless non-radiative mid-range energy transfer, Annals of Physics, vol. 323, 2008, pp. 34-48.
Karalis, Aristeidis, "Electricity Unplugged", Feature: Wireless Energy, Physics World, physicsworld.com, Feb. 2009, pp. 23-25.
Kawamura et al., "Wireless Transmission of Power and Information Through One High-Frequency Resonant AC Link Inverter for Robot Manipulator Applications", IEEE, vol. 32, No. 3, May/Jun. 1996, pp. 503-508.
Konishi, Yoshihiro, Microwave Electronic Circuit Technology, (Marcel Dekker, Inc., New York, NY 1998), Chapter 4, pp. 145-197.
Kurs et al., "Optimized design of a low-resistance electrical conductor for the multimegahertz range," Applied Physics Letters, vol. 98, Apr. 2011, pp. 172504-172504-3.
Kurs et al., "Simultaneous mid-range power transfer to multiple devices", Applied Physics Letters, vol. 96, Jan. 26, 2010, pp. 044102-044102-3.
Kurs et al., "Wireless Power Transfer via Strongly Coupled Magnetic Resonances", Science vol. 317, No. 5834, Jul. 6, 2007, pp. 83-86.
Lamb, Gregory M., "Look, Ma—no wires!—Electricity broadcast through the air may someday run your home", The Christian Science Monitor, http://www.csmonitor.com/2006/1116/p14s01-stct.html, Nov. 15, 2006, 2 pages.
Lee, "Antenna Circuit Design for RFID Applications", Microchip Technology Inc., AN710, Jan. 21, 2003, 50 pages.
Lee, "RFID Coil Design", Microchip Technology Inc., AN678, 1998, 21 pages.
Liang et al., Silicon waveguide two-photon absorption detector at 1.5 μm wavelength for autocorrelation measurements, Applied Physics Letters, vol. 81, No. 7, Aug. 12, 2002, pp. 1323-1325.
Markoff, John, "Intel Moves to Free Gadgets of Their Recharging Cords", The New York Times—nytimes.com, Aug. 21, 2008, 2 pages.
Mediano et al. "Design of class E amplifier with nonlinear and linear shunt capacitances for any duty cycle", IEEE Trans. Microwave Theor. Tech., vol. 55, No. 3, Mar. 2007, pp. 484-492.
Microchip Technology Inc., "MCRF355/360 Reader Reference Design", microID 13.56 MHz Design Guide, 2001, 24 pages.
Minkel, J.R., "Wireless Energy Lights Bulb from Seven Feet Away—Physicists vow to cut the cord between your laptop battery and the wall socket with just a simple loop of wire", Scientific American, http://www.scientificamerican.com/article.cfm?id=wireless-energy-lights-bulb-from-seven-feet-away , Jun. 7, 2007, 1 page.
Minkel, J.R., "Wireless Energy Transfer May Power Devices at a Distance", Scientific American, Nov. 14, 2006, 1 page.
Morgan, James, "Lab report: Pull the plug for a positive charge", The Herald, Web Issue 2680, Nov. 16, 2006, 3 pages.
O'Brien et al., "Analysis of Wireless Power Supplies for Industrial Automation Systems", IEEE, Nov. 2-6, 2003, pp. 367-372.
O'Brien et al., "Design of Large Air-Gap Transformers for Wireless Power Supplies", IEEE, Jun. 15-19, 2003, pp. 1557-1562.
Pendry, J.B., "A Chiral Route to Negative Refraction", Science, vol. 306, Nov. 19, 2004, pp. 1353-1355.
Peterson, Gary, MIT WiTricity Not So Original After All, Feed Line No. 9:, http://www.tfcbooks.com/articles/witricity.htm, accessed on Nov. 12, 2009, pp. 1-3.
Physics Today, "Unwired energy questions asked, answered", Sep. 2007, pp. 16-17.

(56) **References Cited**

OTHER PUBLICATIONS

Physics Today,"Unwired Energy" section in Physics Update, www.physicstoday.org, http://arxiv.org/abs/physics/0611063, Jan. 2007, pp. 26.
Powercast L.L.C., "White Paper", Powercast simply wire free, 2003, 2 pages.
PR News wire, "The Big Story for CES 2007: The public debut of eCoupled Intelligent Wireless Power", Press Release, Fulton Innovation LLC, Las Vegas, NV, Dec. 27, 2006, 3 pages.
Press Release, "The world's first sheet-type wireless power transmission system: Will a socket be replaced by e-wall?", Public Relations Office, School of Engineering, University of Tokyo, Japan, Dec. 12, 2006, 4 pages.
PressTV, "Wireless power transfer possible", http://edition.presstv.ir/detail/12754.html, Jun. 11, 2007, 1 page.
Reidy, Chris (Globe staff), "MIT discovery could unplug your iPod forever", Boston.com, http://www.boston.com/business/ticker/2007/06/mit_discovery_c.html, Jun. 7, 2007, 3 pages.
Risen, Clay, "Wireless Energy", The New York Times, Dec. 9, 2007, 1 page.
Sakamoto et al., A Novel Circuit for Non-Contact Charging Through Electro-Magnetic Coupling, IEEE, Jun. 29-Jul. 3, 1992, pp. 168-174.
Scheible et al., "Novel Wireless Power Supply System for Wireless Communication Devices in Industrial Automation Systems", IEEE, Nov. 5-8, 2002, pp. 1358-1363.
Schneider, David, "Electrons Unplugged. Wireless power at a distance is still far away," IEEE Spectrum, May 2010, pp. 35-39.
Schuder et al., "An Inductively Coupled RF System for the Transmission of 1 kW of Power Through the Skin", IEEE Transactions on Bio-Medical Engineering, vol. BME-18, No. 4, Jul. 1971, pp. 265-273.
Schuder et al., "Energy Transport Into the Closed Chest From a Set of Very-Large Mutually Orthogonal Coils", Communication Electronics, vol. 64, Jan. 1963, pp. 527-534.
Schuder, John C., "Powering an Artificial Heart: Birth of the Inductively Coupled-Radio Frequency System in 1960", Artificial Organs, vol. 26, No. 11, Nov. 2002, pp. 909-915.
Schutz et al., "Load Adaptive Medium Frequency Resonant Power Supply", IEEE, Nov. 2002, pp. 282-287.
Sekitani et al., "A large-area flexible wireless power transmission sheet using printed plastic MEMS switches and organic field-effect transistors".Dec. 11-13, 2006, 1-3 [Publication Unknown] Possible source, need to check w D. Peterson: IEDM '06. International Electron Devices Meeting, 2006, Dec. 11-13, 2006, 4 pages.
Sekitani et al., "A large-area wireless power-transmission sheet using printed organic transistors and plastic MEMS switches", Nature Materials 6: 413-417 (Jun. 1, 2007) Published online Apr. 29, 2007, 5 pages.
Sekiya et al. "FM/PWM control scheme in class DE inverter", IEEE Trans. Circuits Syst. I, vol. 51, No. 7, Jul. 2004, pp. 1250-1260.
Senge, Miebi, "MIT's wireless electricity for mobile phones", Vanguard, http://www.vanguardngr.com/articles/2002/features/gsm/gsm211062007.htm, Jun. 11, 2007, 1 page.
Sensiper, S., "Electromagnetic wave propogation on helical conductors", Technical Report No. 194 (based on PhD thesis), Massachusetts Institute of Technology, May 16, 1951, 126 pages.
Soljacic et al., "Photonic-crystal slow-light enhancement of nonlinear phase sensitivity", J. Opt. Soc. Am B, vol. 19, No. 9, Sep. 2002, pp. 2052-2059.
Soljacic et al., "Wireless Energy Transfer Can Potentially Recharge Laptops, Cell Phones Without Cords", Nov. 14, 2006, 3 pages.
Soljacic, "Wireless Non-Radiative Energy Transfer", PowerPoint presentation, Massachusetts Institute of Technology, Oct. 6, 2005, 14 pages.
Soljacic, Marin, "Wireless nonradiative energy transfer", Visions of Discovery New Light on Physics, Cosmology, and Consciousness, Cambridge University Press, New York, 2011, pp. 530-542.
Someya, Takao, "The world's first sheet-type wireless power transmission system", Press Interview Handout, University of Tokyo, Dec. 12, 2006, 18 pages.
Staelin et al., Electromagnetic Waves, (Prentice Hall Upper Saddle River, New Jersey, 1998), Chapters 2, 3, 4, and 8, pp. 46-176 and 336-405.
Stark III, Joseph C., "Wireless Power Transmission Utilizing a Phased Array of Tesla Coils", Master Thesis, Massachusetts Institute of Technology, 2004, 247 pages.
Tesla, Nikola, "High Frequency Oscillators for Electro-Therapeutic and Other Purposes", Proceedings of the IEEE, vol. 87, No. 7, Jul. 1999, pp. 1282-1292.
Tesla, Nikola, "High Frequency Oscillators for Electro-Therapeutic and Other Purposes", The Electrical Engineer, vol. XXVI, No. 50, Nov. 17, 1898, 11 pages.
Texas Instruments, "HF Antenna Design Notes", Technical Application Report, Literature No. 11-08-26-003, Sep. 2003, 47 pages.
Thomsen et al., "Ultrahigh speed all-optical demultiplexing based on two-photon absorption in a laser diode", Electronics Letters, vol. 34, No. 19, Sep. 17, 1998, pp. 1871-1872.
U.S. Appl. No. 60/698,442, "Wireless Non-Radiative Energy Transfer", filed Jul. 12, 2005, 14 pages.
U.S. Appl. No. 60/908,666, "Wireless Energy Transfer", filed Mar. 28, 2007, 108 pages.
U.S. Appl. No. 60/908,383, "Wireless Energy Transfer", filed Mar. 27, 2007, 80 pages.
UPM Rafsec, "Tutorial overview of inductively coupled RFID Systems", http://www.rafsec.com/rfidsystems.pdf, May 2003, 7 pages.
Vandevoorde et al., "Wireless energy transfer for stand-alone systems: a comparison between low and high power applicability", Sensors and Actuators A 92, Jul. 17, 2001, pp. 305-311.
Vilkomerson et al., "Implantable Doppler System for Self-Monitoring Vascular Grafts", IEEE Ultrasonics Symposium, Aug. 23-27, 2004, pp. 461-465.
Yariv et al., "Coupled-resonator optical waveguide: a proposal and analysis", Optics Letters, vol. 24, No. 11, Jun. 1, 1999, pp. 711-713.
Zierhofer et al., "High-Efficiency Coupling-Insensitive Transcutaneous Power and Data Transmission Via an Inductive Link", IEEE Transactions on Biomedical Engineering, vol. 37, No. 7, Jul. 1990, pp. 716-722.
Australian Patent Examination Report No. 1 for Australian Application No. 2011312376 dated May 26, 2014 (3 pages).
Supplementary European Search Report for Application No. 11831382 dated Jan. 26, 2015 (8 pages).
PCT/US2013/065963, International Application No. PCT/US2013/065963, International Search Report and Written Opinion, mailed on Oct. 29, 2014, 14 pages.
PCT/US2013/065963, International Application No. PCT/US2013/065963, International Preliminary Report on Patentability, mailed on Apr. 30, 2015, 11 pages.
Canadian Office Action for Application No. 2,813,678 dated Feb. 24, 2015 (4 pages).
Japanese Office Action for Japanese Application No. 2013-532855 dated Mar. 2, 2015 (9 pages).
The State Intellectual Property Office of the People's Republic of China, English Translation of the Notification of the First Office Action issued on Dec. 1, 2014 for CN Appl. No. CN201180055093.2, 41 pages.
Chinese Office Action for Chinese Application No. 2012800496010 dated Dec. 21, 2015 (5 pages).
EP Search Report for EP Application No. 15 19 0252 dated Jan. 4, 2016 (11 pages).
Communication from the European Patent Office for Application No. 11 831 382.4 dated Feb. 1, 2016 (5 pages).
Korean Office Action for Korean Application No. 10-2013-7009960 dated Mar. 7, 2016 (13 pages).
Australian Patent Examination Report No. 1 for Australian Patent Application No. 2012305688, dated May 11, 2016 (3 pages).

* cited by examiner

Fig. 1

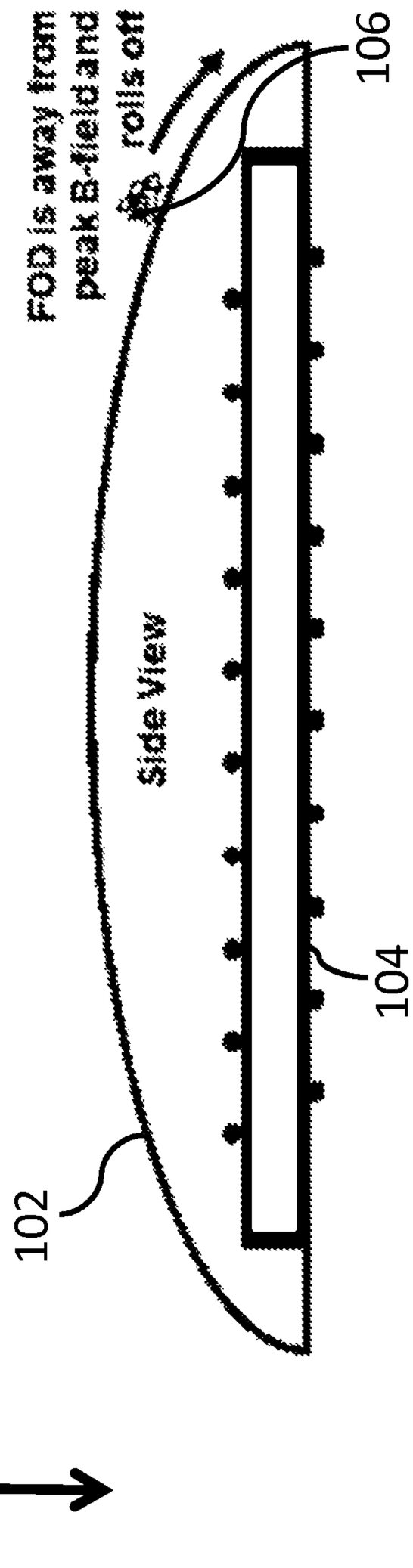
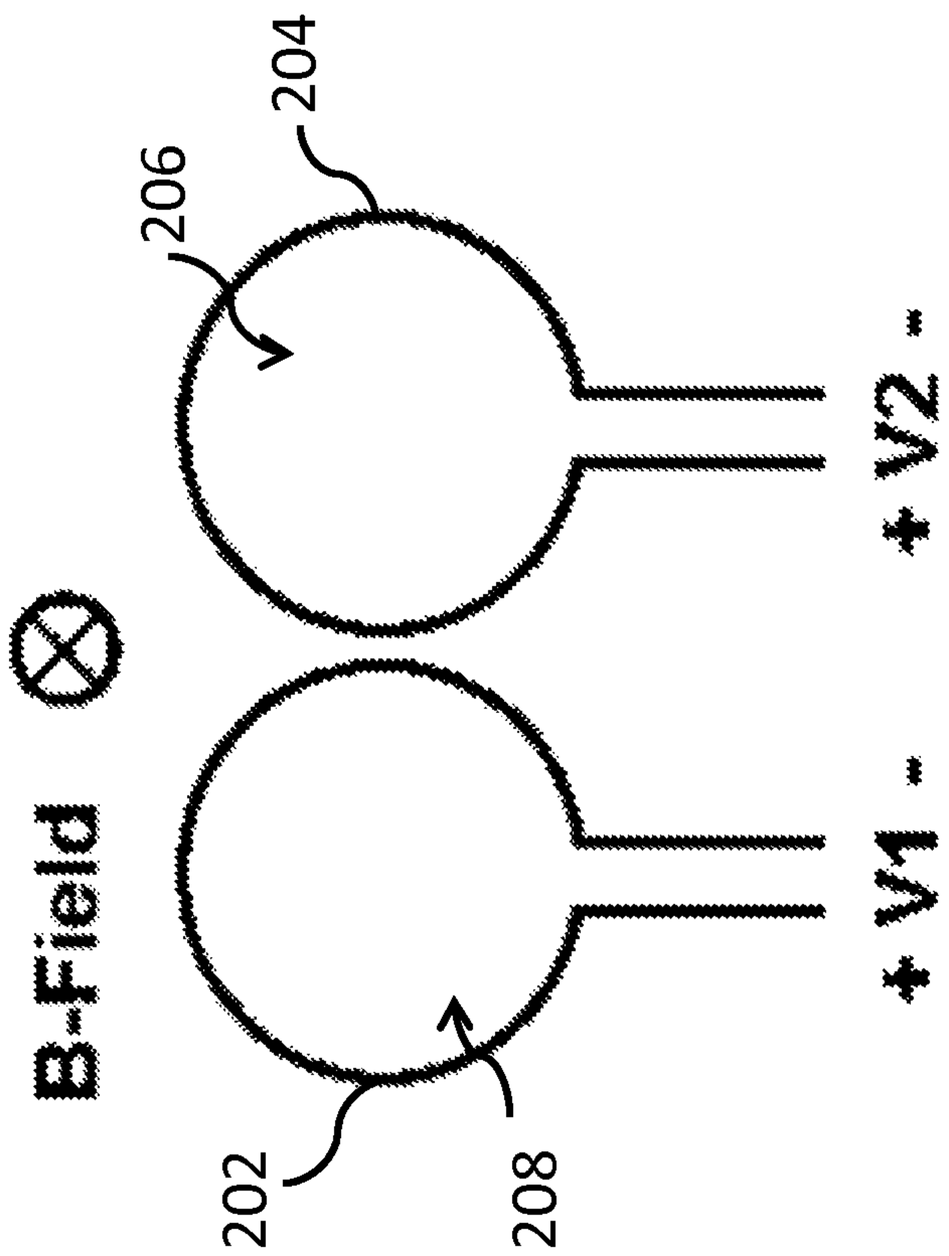

FOD is away from peak B-field and rolls off
106
Side View
104
102
Gravity

Fig. 2



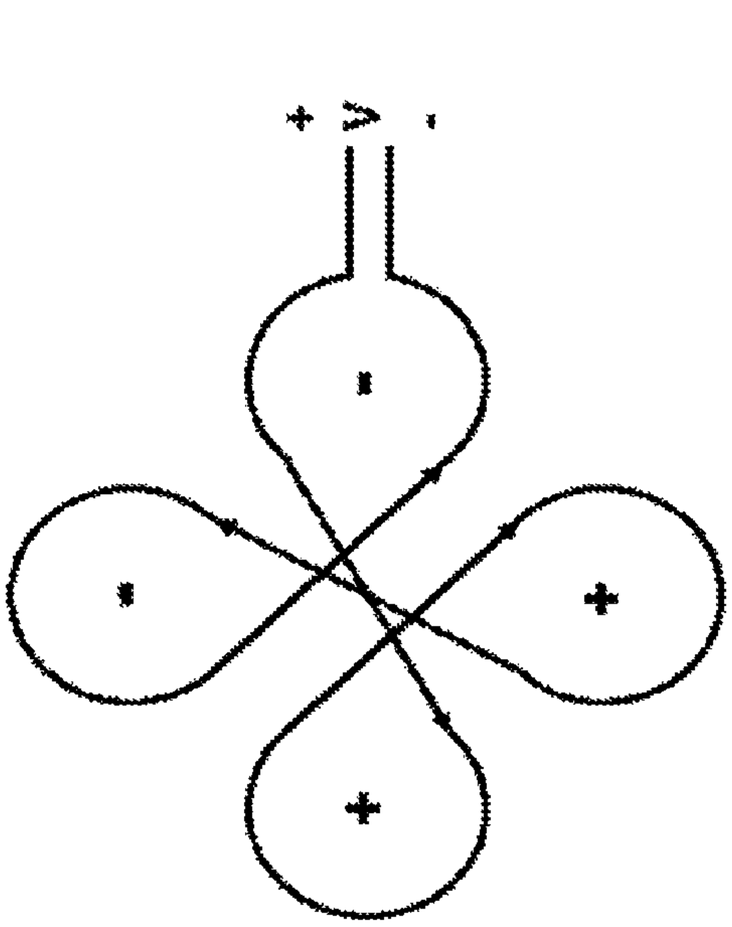


Fig. 3B

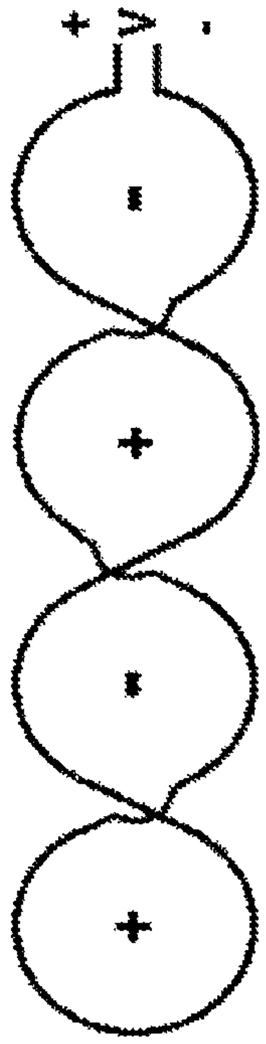


Fig. 3D

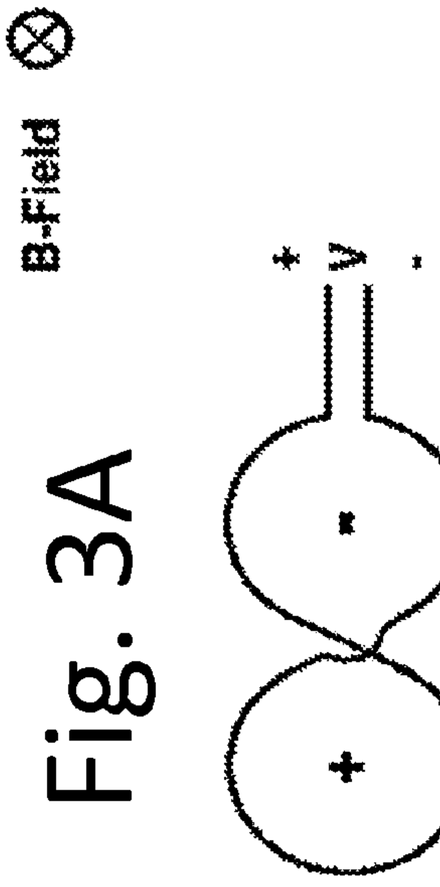


Fig. 3A

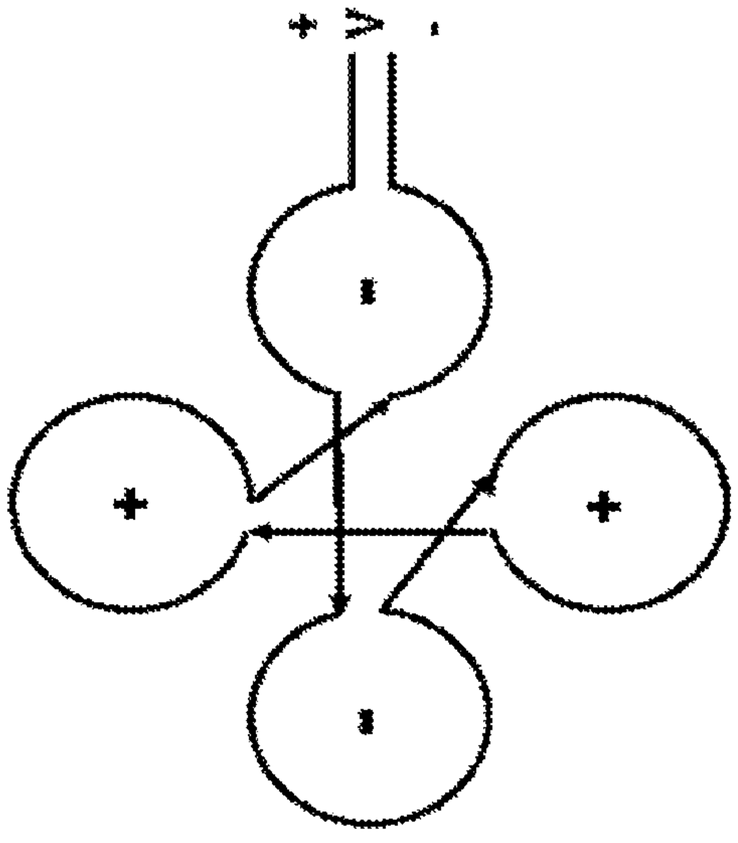


Fig. 3C

Fig. 4A

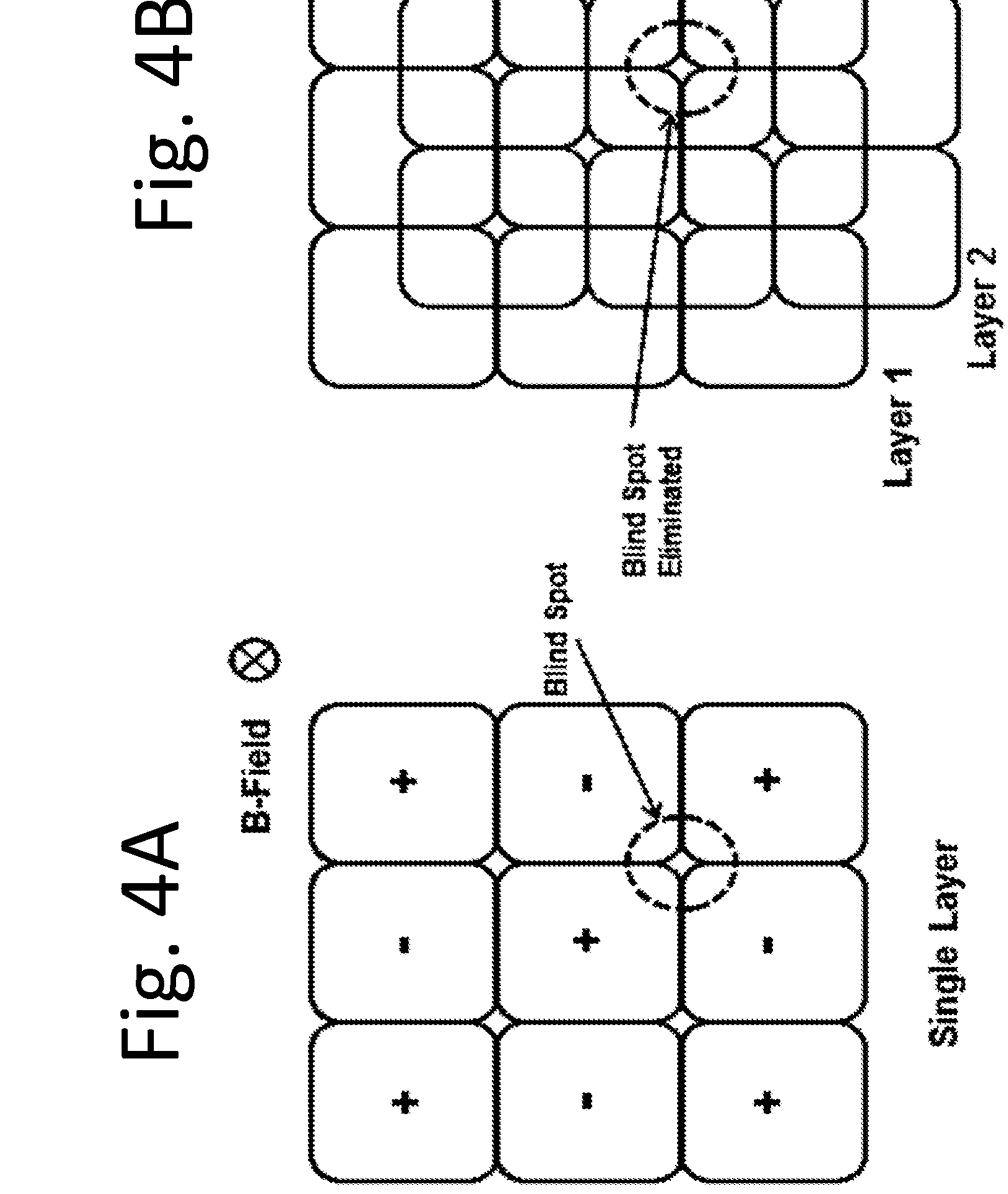

B-Field
Blind Spot
+
-
+
-
+
-
+
-
+
-
+
-
Single Layer

Fig. 4B

Blind Spot
Eliminated
Layer 1
Layer 2

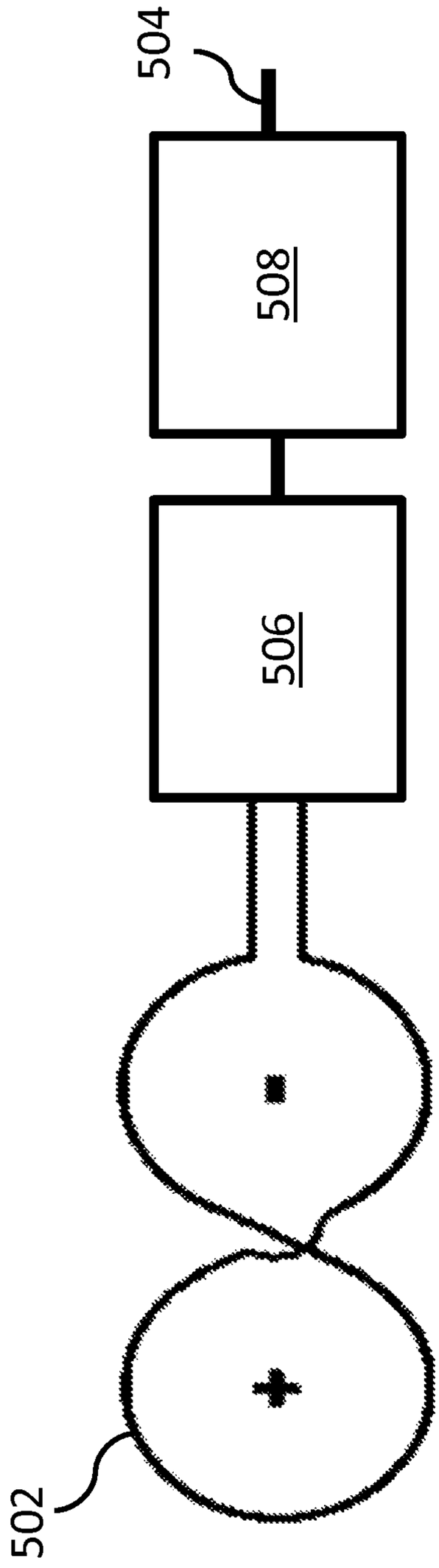
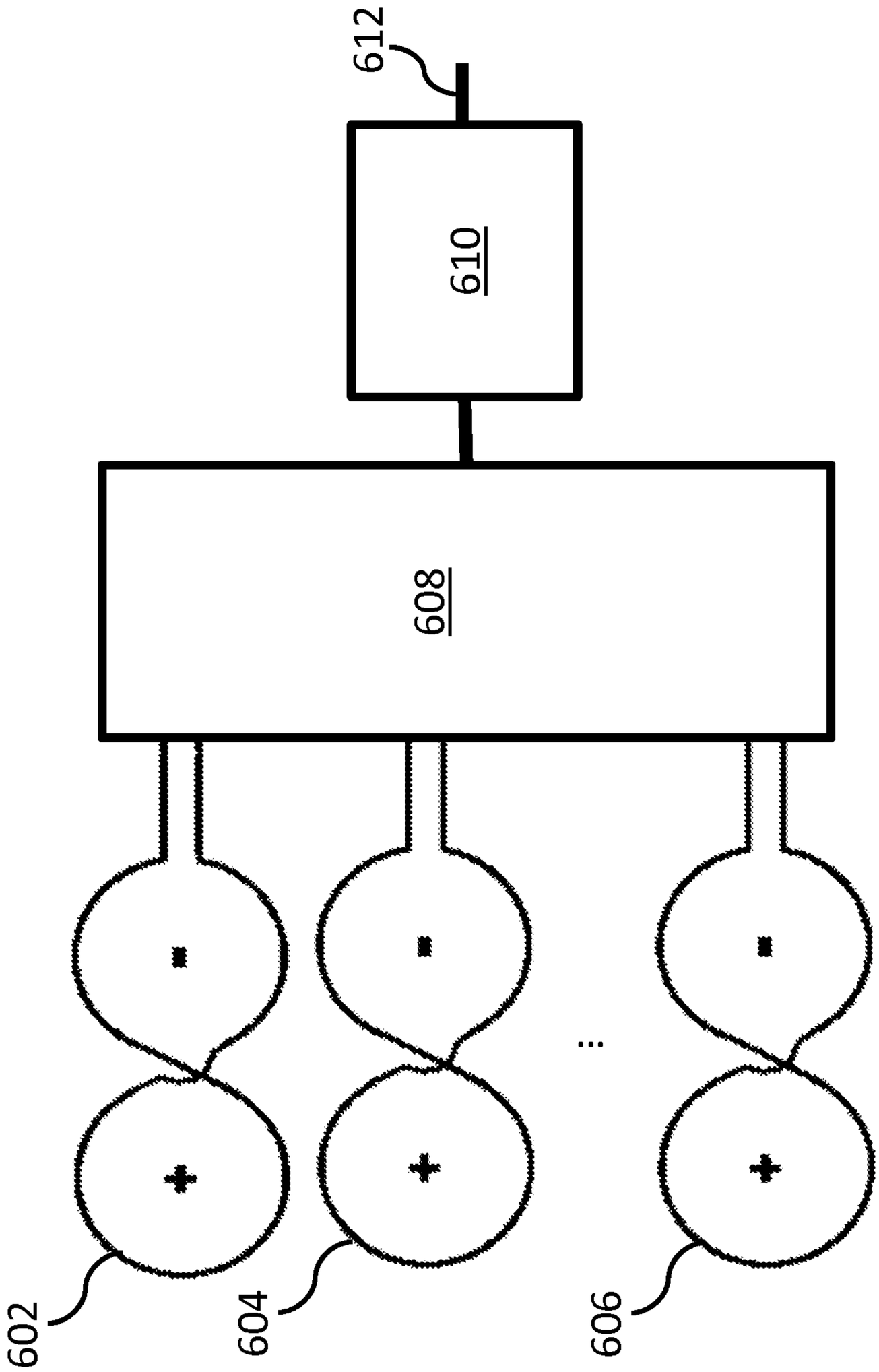


Fig. 5

Fig. 6



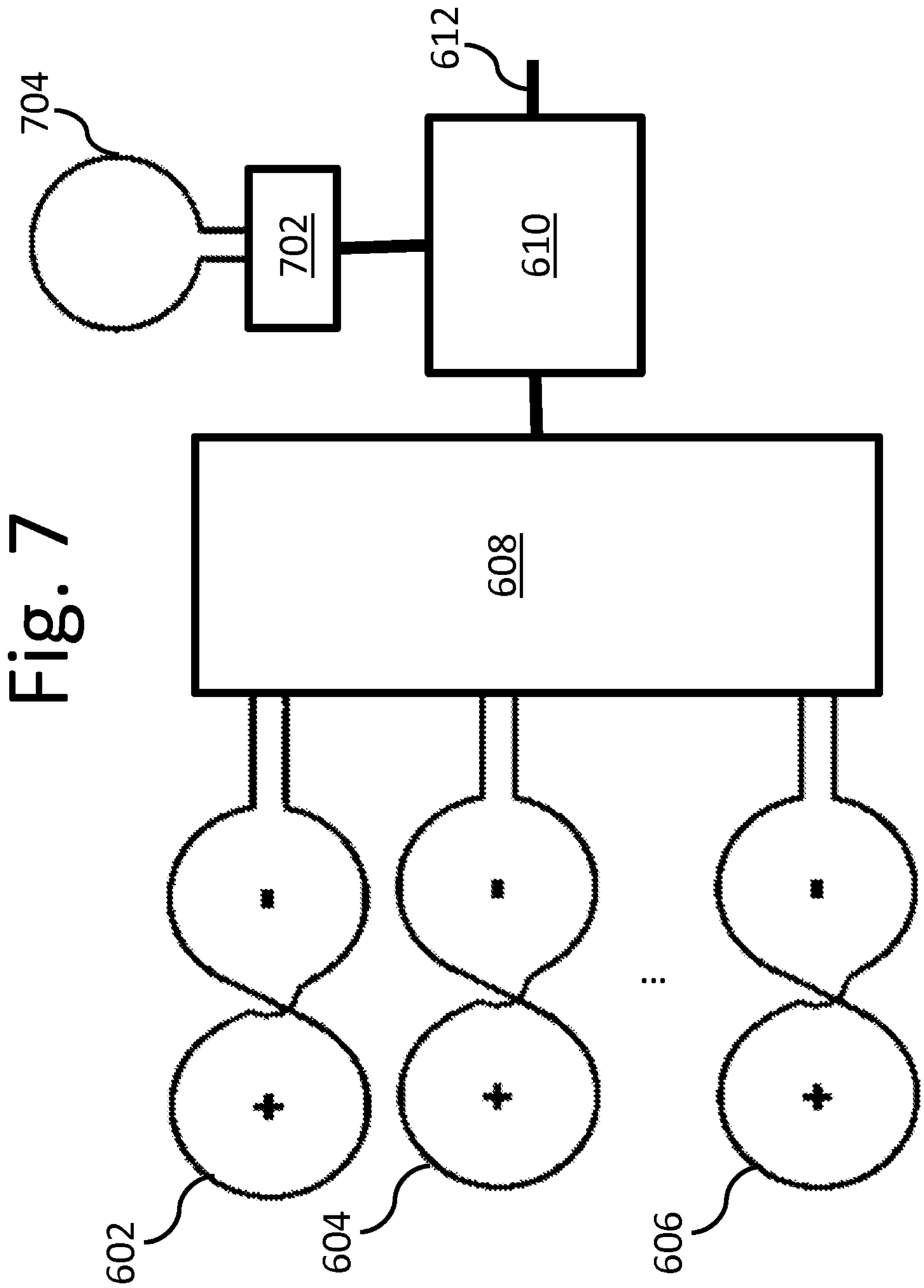
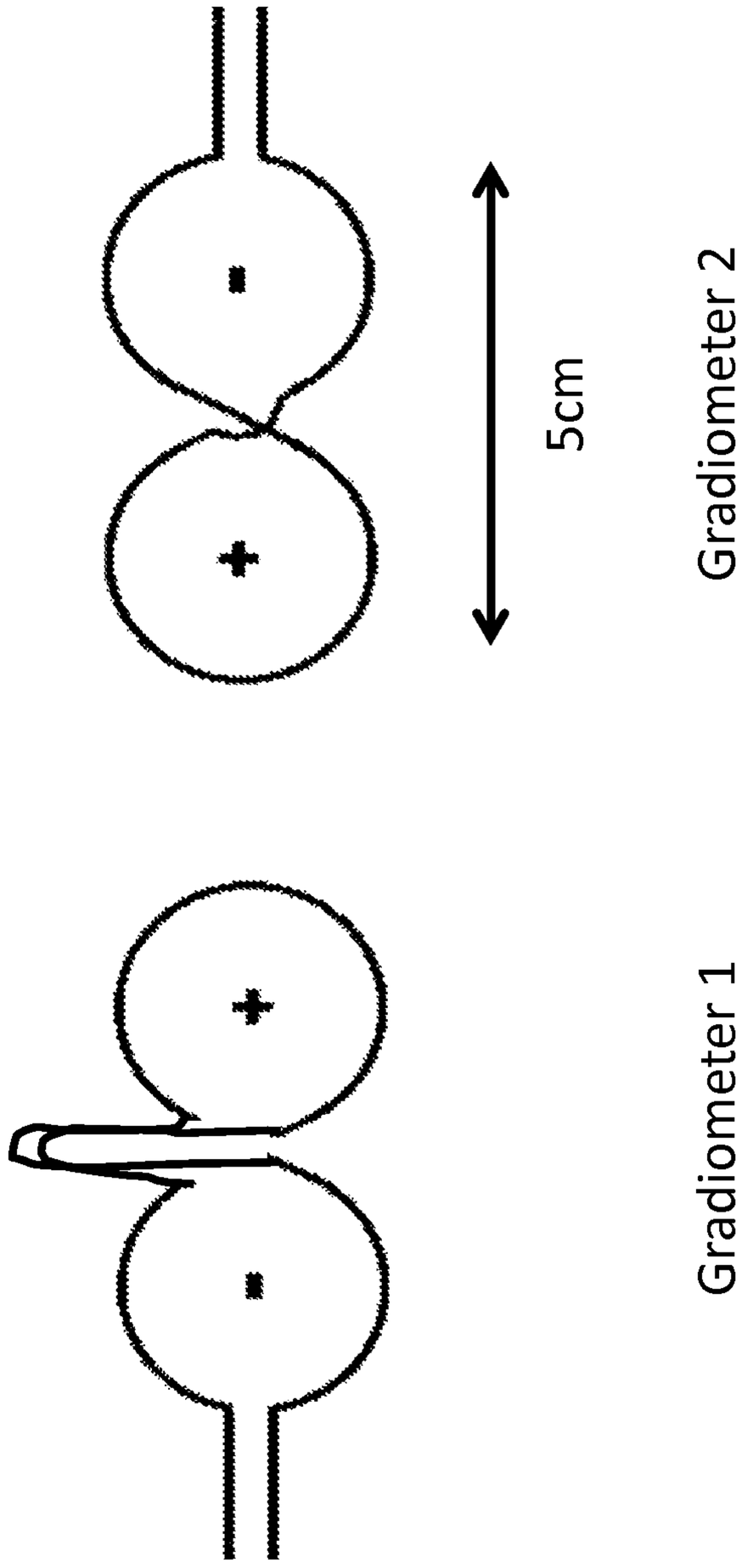


Fig. 7

Fig. 8



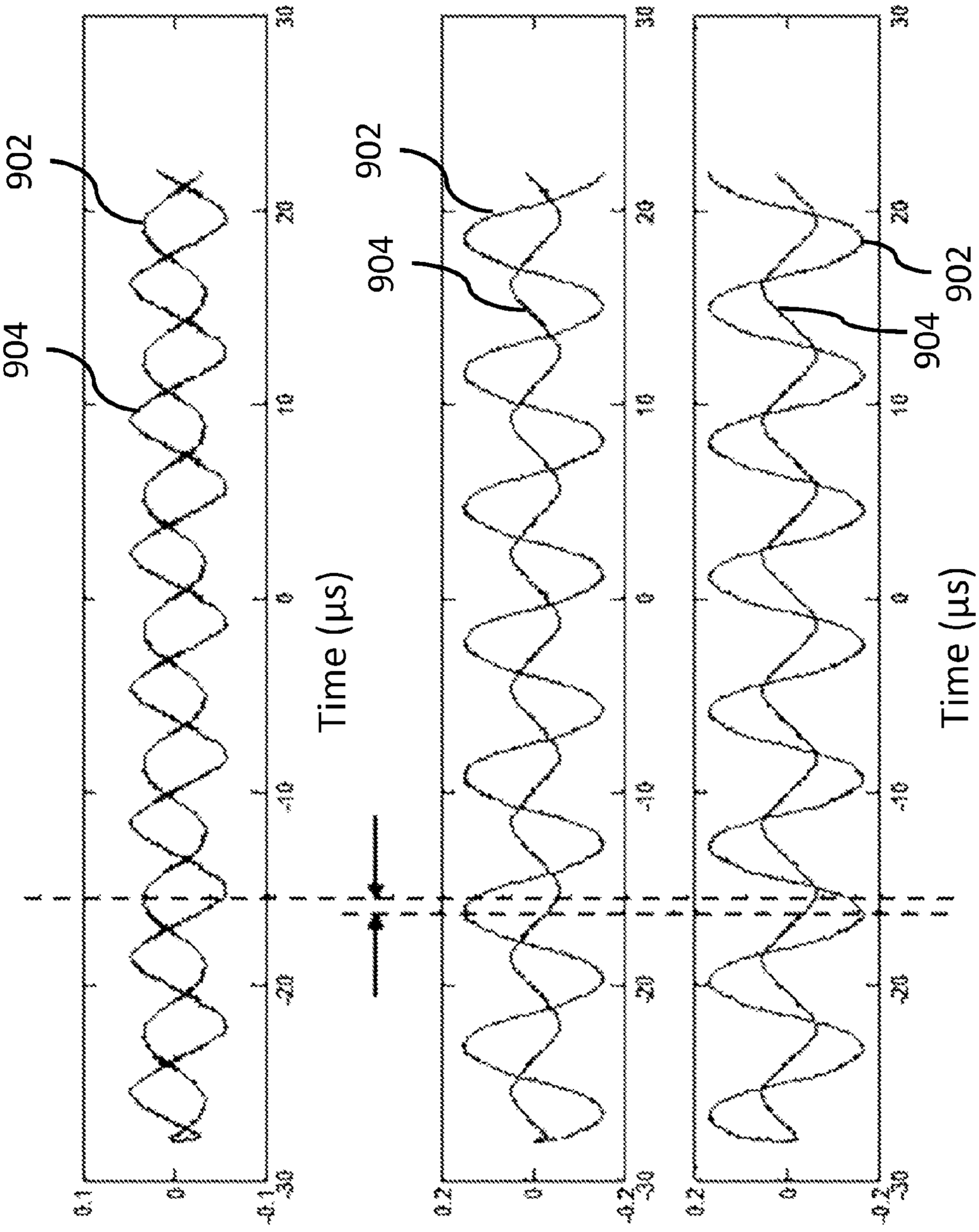
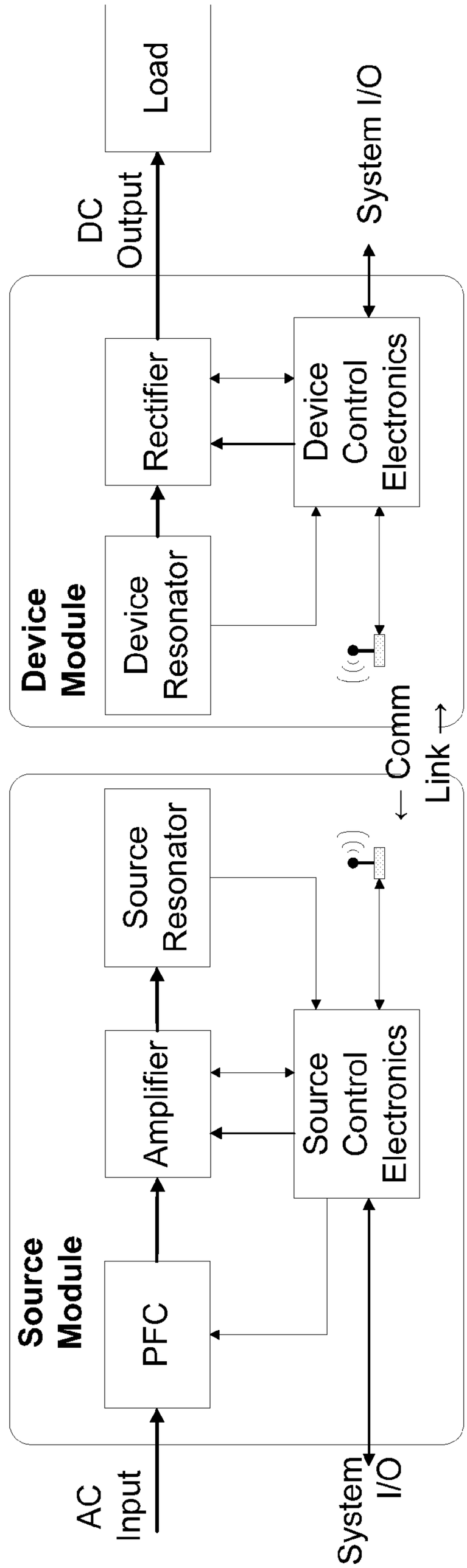


Fig. 9A

Fig. 9B

Fig. 9C

Fig. 10


Load
DC Output
System I/O
Device Module
Rectifier
Device Control Electronics
Device Resonator
Comm Link
Source Resonator
Amplifier
Source Control Electronics
Source Module
PFC
AC Input
System I/O

FOREIGN OBJECT DETECTION IN WIRELESS ENERGY TRANSFER SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. provisional patent application 61/532,785 filed Sep. 9, 2011.

BACKGROUND

1. Field

This disclosure relates to wireless energy transfer and methods for detecting foreign object debris (FOD) on wireless power transmission systems.

2. Description of the Related Art

Energy or power may be transferred wirelessly using a variety of known radiative, or far-field, and non-radiative, or near-field, techniques as detailed, for example, in commonly owned U.S. patent application Ser. No. 12/613,686 published on May 6, 2010 as US 2010/010909445 and entitled "Wireless Energy Transfer Systems," U.S. patent application Ser. No. 12/860,375 published on Dec. 9, 2010 as 2010/0308939 and entitled "Integrated Resonator-Shield Structures," U.S. patent application Ser. No. 13/222,915 published on Mar. 15, 2012 as 2012/0062345 and entitled "Low Resistance Electrical Conductor," U.S. patent application Ser. No. 13/283,811 published on Oct. 28, 2011 as 20120248981 and entitled "Multi-Resonator Wireless Energy Transfer for Lighting," the contents of which are incorporated by reference.

Wireless charging systems that rely on an oscillating magnetic field between two coupled resonators can be efficient, non-radiative, and safe. Non-magnetic and/or non-metallic objects that are inserted between the resonators may not substantially interact with the magnetic field used for wireless energy transfer. In some embodiments, users of wireless power transfer systems may wish to detect the presence of these "foreign objects" and may wish to control, turn down, turn off, alarm, and the like, the wireless power transfer system. Metallic objects and/or other objects inserted between the resonators may interact with the magnetic field of the wireless power transfer system in a way that causes the metallic and/or other objects to perturb the wireless energy transfer and/or to heat up substantially. In some embodiments, users of wireless power transfer systems may wish to detect the presence of these "foreign objects" and may wish to control, turn down, turn off, alarm, and the like, the wireless power transfer system.

Foreign Object Debris (FOD) positioned in the vicinity of wireless power transmission systems can be benign and/or may interact with the fields used for energy transfer in a benign way. Examples of benign FOD may include dirt, sand, leaves, twigs, snow, grease, oil, water, and other substances that may not interact significantly with a low-frequency magnetic field. In embodiments, FOD may include objects that may interact with the fields used for wireless energy transfer in a benign way, but that may be restricted from the region very close to the resonators of the wireless transfer systems because of perceived danger, or out of a preponderance of caution. A common example of this type of FOD is a cat that may wish to sleep between the coils of a wireless EV charging system for example. In embodiments, some FOD may interact with the magnetic field in a way that may perturb the characteristics of the resonators used for energy transfer, may block or reduce the magnetic fields used for energy transfer, or may create a fire and or burning hazard. In some applications special precautions may be necessary to avoid combustible metallic objects becoming hot enough to ignite during high-power charging. Some metallic objects can heat up and have enough heat capacity to cause a burn or discomfort to a person who might pick them up while they are still hot. Examples include tools, coils, metal pieces, soda cans, steel wool, food (chewing gum, burgers, etc.) wrappers, cigarette packs with metal foil, and the like.

Thus what are needed are methods and designs for detecting or mitigating the effects of FOD in the vicinity of the wireless energy transfer system.

SUMMARY

In accordance with exemplary and non-limiting embodiments, a foreign object debris detection system may measure perturbations in the magnetic field around the resonators of a wireless energy transfer system using magnetic field sensors and/or gradiometers. The sensors and/or gradiometers may be positioned in the magnetic field of a wireless energy transfer system. The sensors and/or gradiometers may comprise loops of wire and/or printed conductor traces forming loops, figure-8 loops, and/or structures comprising one loop or multiple loops that generate an electrical signal proportional to the amount of magnetic flux crossing its surface. The loop and/or loops may be connected to high-input-impedance readout circuitry. The readout circuitry may measure the voltage and/or the current and/or the relative phase of the voltages and/or currents in the loops. In embodiments the system may include multiple layers of loops to increase the detection probability of FOD. In embodiments, the loops may be designed to operate without significantly affecting characteristics of the wireless power transfer system such as the perturbed quality factors of the resonators, the efficiency of the energy transfer, the amount of power transferred, the amount of heat generated by the system, and the like.

In accordance with exemplary and non-limiting embodiments, there is provided a wireless energy transfer system may comprise foreign object debris detection system. The system may include at least one wireless energy transfer source configured to generate an oscillating magnetic field. The foreign object debris may be detected by a field gradiometer positioned in the oscillating magnetic field. The voltages and/or currents of the field gradiometers may be measured using readout circuitry and a feedback loop based on the readings from the gradiometers may be used to control the parameters of the wireless energy source.

BRIEF DESCRIPTION OF FIGURES

FIG. **1** shows a side view of a resonator with a resonator cover providing passive FOD mitigation.

FIG. **2** two loops of wire that may be used as individual field sensors and that may be fashioned into a gradiometer that senses the difference in the magnetic flux capture by the two individual field sensors.

FIG. **3**A shows a two-lobe configuration of two small conductor loops arranged to have opposed magnetic dipoles, (such a structure may be referred to as a magnetic quadrupole); **3**B shows a 4-lobe configuration of aligned magnetic quadrupoles; **3**C shows a 4-lobe configuration of opposed quadrupoles, sometimes referred to as an octupole; and **3**D shows a 4-lobe configuration extending in a linear dimension. The "+" and "−" signs indicate the direction of the magnetic dipole of each loop, in a relative reference frame

FIG. **4**A shows a FOD detector array comprising loops with a square shape to achieve high area-fill factor; and **4**B shows an embodiment with two offset arrays, an arrangement that may be used to eliminate blind spots.

FIG. **5** shows a FOD detector connected to a readout circuit.

FIG. **6** shows an array of FOD detectors connected to readout circuitry.

FIG. **7** shows an array of FOD detectors connected to readout circuitry and a synchronization loop.

FIG. **8** shows an example embodiment of FOD detector loops.

FIG. **9**A-**9**C shows example voltage measurement curves from a figure-8 gradiometer sensor.

FIG. **10** shows a block diagram of an exemplary EV charger system.

DETAILED DESCRIPTION

Methods for mitigating FOD risks can be categorized as passive mitigation techniques and active mitigation techniques. Passive mitigation techniques may be used to prevent FOD from entering or remaining in the regions of high magnetic field. Passive mitigation techniques may lower the likelihood of FOD interacting hazardously with magnetic fields. Active mitigation techniques may be used detect and react to the presence of FOD.

Passive Mitigation Techniques

Passive mitigation techniques may be used to keep FOD from entering the regions between resonators or specific regions of high magnetic field, thereby preventing the interaction of the FOD with the magnetic fields.

By way of additional exemplary embodiments, the design of a resonator cover in a wireless power transfer system may provide a passive FOD mitigation technique. In embodiments the enclosure of a source and/or device and/or repeater resonator may be shaped to prevent FOD from coming close to the areas of the resonators and/or the resonator coils where the magnetic field may be large. A resonator enclosure may be designed to be curved, angled, or shaped to force any FOD on the cover to roll off the cover and away from the resonator and/or high magnetic fields. The resonator enclosure may be shaped or positioned to allow gravity to pull objects away from the resonators. In other embodiments the enclosures and position of the resonators may be designed to use other natural or omnipresent forces to move FOD away. For example, the force of water currents, wind, vibration, and the like may be used to prevent FOD from accumulating or staying in unwanted regions around resonators. In embodiments, the resonators may be arranged to be substantially perpendicular to the ground so that objects may not naturally rest and accumulate on the resonators. In embodiments, the resonator enclosure may include a keep-out zone providing for a minimum distance between FOD and the resonator components. The keep-out zone may be sufficiently large to ensure that the fields at the outside of the keep-out zone are sufficiently small to not cause safety or performance concerns.

An example resonator cover providing a degree of passive FOD protection is shown in FIG. **1**. A magnetic resonator **104** of a wireless power transfer system may be surrounded with or enclosed by or placed under a shaped cover **102**. The cover **102** may be shaped to force FOD **106** to roll down the cover **102** due to the force of gravity. The shape of the cover **102** may prevent FOD **106** from accumulating on top of the cover **102** and/or in the vicinity of the resonator **104** by forcing any FOD to the sides of the resonator and/or away from the regions surrounding the resonator where the magnitude of the magnetic fields is high enough to cause a hazardous condition due to heating of the FOD. In embodiments, the FOD may be forced far enough away from the high field regions to no longer pose a risk of being heated and/or ignited by the fields.

In other exemplary and non-limiting embodiments, a passive FOD technique may include sizing the resonators and/or resonator components to reduce the maximum magnetic field density anywhere in the region of wireless power exchange below a desired limit. In embodiments, relatively large resonator coils may be used to mitigate a subset of FOD risks. For a fixed level of power transfer the use of larger resonator coils may be used to reduce the magnetic field strength per unit area required to transfer a certain amount of power wirelessly. For example, the maximum magnetic field strength generated by a source may be reduced below a threshold where heating or other hazards may be known to occur. Passive mitigation techniques may not always be possible or practical or sufficient. For example, reducing a FOD hazard by increasing a resonator size may not be practical owing to the system cost restraints or to the desire to integrate a resonator into a system of a specified volume. However, even in applications where a completely passive technique may not be possible, practical and/or sufficient, passive mitigation techniques may be used to at least partially reduce the FOD risk and may be complementary to active mitigation techniques.

Active Mitigation Techniques

In accordance with exemplary and non-limiting embodiments, an active mitigation technique for FOD may include a detector system that may detect metallic objects, hot objects, perturbations in resonator parameters, and/or perturbations in magnetic field distributions.

In accordance with exemplary and non-limiting embodiments, FOD objects, such as metallic objects, may be of sufficient size, extent, and/or material composition to perturb the efficiency or power transfer capabilities of a wireless energy transfer system. In such cases, the presence of said FOD objects may be determined by examining the change in one or more of the voltage, current, and/or power associated with the source resonator and/or device resonator and/or repeater resonator of a wireless power system. Some FOD objects may perturb the parameters of the resonators used for energy transfer and/or may perturb the characteristics of the energy transfer. A FOD object may change the impedance of a resonator for example. In accordance with exemplary and non-limiting embodiments, these perturbations may be detected by measuring the voltage, current, power, phase, frequency, and the like of the resonators and the wireless energy transfer. Changes or deviations from expected or predicted values may be used to detect the presence of FOD. In an exemplary embodiment, dedicated FOD sensors may not be needed to detect and react to FOD in a wireless power system.

In accordance with exemplary and non-limiting embodiments, FOD objects may only weakly perturb the wireless energy transfer and may not be substantially detectable by monitoring electrical parameters of the resonators and/or the characteristics of the wireless energy transfer. Such objects can still create a hazard, however. For example, a FOD object that only weakly interacts with the magnetic field may still heat up substantially. An example of a FOD object that may only weakly interact with the magnetic field but that may experience significant heating is a metal-foil-and-paper wrapper such as is often found in chewing gum and cigarette packages and as is often used to wrap food from fast food

establishments such as Burger King and Kentucky Fried Chicken. When placed between the resonators of a 3.3-kW wireless energy vehicle charging system, a chewing gum wrapper may not be detectable by examining the electrical parameters associated with the resonators and/or the energy transfer system. However, said wrapper may still absorb enough power to rapidly heat and for the paper to eventually burn.

In accordance with exemplary and non-limiting embodiments, an active mitigation system for FOD may comprise temperature sensors to detect hot spots, hot areas, and/or hot objects near by the wireless energy transfer system. A system may comprise any number of temperature sensors, infrared detectors, cameras, and the like to detect a heat source, heat gradient and the like around the energy transfer system. In embodiments, hot object sensing may be used alone or in addition to other active and passive mitigation techniques and can be used to further improve the detectability of heated FOD and/or reduce the false-alarm rate of other active FOD systems.

In accordance with exemplary and non-limiting embodiments, an active mitigation system for FOD objects that only weakly perturb the magnetic field between two resonators may comprise sensors for measuring small changes in the magnetic field in the proximity of the FOD objects. For example, a metal-foil-and-paper chewing gum wrapper may not substantially alter the magnetic flux between two resonators, but it might substantially alter the magnetic flux through a much smaller sensor coil or loop if it covered and/or blocked any portion of the coil or loop area. In embodiments, local disturbances in the magnetic field caused by the presence of FOD may be detected by measuring magnetic field changes, variations, gradients, and the like, in the vicinity of the FOD.

In accordance with exemplary and non-limiting embodiments, a FOD sensor may be realized using two small wire loops **202**, **204** as shown in FIG. **2**. Such a sensor may be placed on or near the resonators used for wireless energy transfer. During operation the wireless energy transfer system generates a magnetic field that passes through the two loops. Each individual loop develops a voltage proportional to the amount of magnetic flux threading the inside of each loop **206**, **208**. The difference between the voltages developed by the two loops is, to first order, proportional to the gradient of the magnetic field in proximity to the loops. If the two loops are placed in a region of uniform field and the loops are substantially similar, then the difference between the voltages developed by the two loops may be very small. If, for example, a chewing gum wrapper is placed so that it partially covers one of the loops but not the other, then the difference in voltage developed by the two loops will be larger than when the wrapper was not present because the metallic foil of the gum wrapper may deflect or/or absorb some of the magnetic flux that would have normally passed through that loop. In embodiments, the output from the two loops may be subtracted from each other so that the combination of loops produces a small signal when the sensed field is substantially uniform, and a measurably larger signal when there is a gradient in the field between the two loops. When the loops and/or coils are configured to generate a signal in the presence of a field gradient, they may be referred to as being arranged as a gradiometer. Note the signals from the loops may be subtracted using analog circuitry, digital circuitry and/or by connected the loops together in a specific configuration. The sensitivity of the sensor and/or gradiometer may be related to the magnitude and/or phase of the voltage difference between the two loops.

In accordance with exemplary and non-limiting embodiments, the sensitivity of the sensor and/or gradiometer may be adjusted to preferentially detect objects of a given size, or above a given size. The sensitivity may be adjusted to reduce false detection rates, to lower the noise of the detection system, and/or to operate over a range of frequencies. In embodiments the size and shape of the loops may be adjusted to adjust the sensitivity of the sensor. The loops may be adjusted to comprise more turns and or to comprise additional loops, such as four loops, or eight loops for example. In embodiments, the loops may be positioned to have rotational symmetry or they may be arranged in a linear arrangement or they may be shaped to fill a region of any size and shape.

In embodiments where the field density may be non-uniform in the locations where gradiometers may be placed and/or where other gradiometer and/or loop designs may be implemented, the presence of metallic objects may result in amplitude and/or phase changes in the waveform corresponding to the difference between the two loop voltages. In embodiments, the loops may have a plurality of turns. In accordance with exemplary and non-limiting embodiments, the loop areas **206**, **208** may be sized according to the magnetic field strength of the wireless energy transfer system, the desired sensitivity of the detection method, the complexity of the system and the like. If the metallic FOD is substantially smaller than the loop area, only a weak signal may arise when the FOD is present. This weak signal may risk being overwhelmed by noise or interfering signals. If the loop is sized to be on the order of (e.g. within a factor of 3) of the minimum FOD size to be detected, then the signal may be sufficiently large for detection with low false-alarm rate. In embodiments, a FOD sensor and/or gradiometer may comprise one or more loops of different sizes, shapes and/or arrangements. In embodiments, a FOD sensor may comprise regions with one sensor, more than one sensor or no sensor.

In accordance with exemplary and non-limiting embodiments, another way to measure a field gradient in the vicinity of a metallic object may be to create a coil (also referred to as a loop) in a fashion that directly outputs a voltage that is proportional to the local gradient in the magnetic field. Such a coil serves the purpose of the two coils depicted in FIG. **2**, but requires only one voltage measurement. If, for example, one were to double the area of one of the loops depicted in FIG. **2** and then twist it into a figure-8 shape where each lobe of the figure-8 had approximately equal area, but the current induced in each loop by the local magnetic field traveled in the opposing directions, then the voltage developed across its two terminals would be proportional to the difference in magnetic flux between the two lobes. FIG. **3**A-**3**D depicts some exemplary configurations of twisted loops that may be capable of directly outputting a voltage that is proportional to the local gradient in the magnetic field.

The two loops shown in FIG. **2** may be referred to as magnetic dipoles and the loops in FIG. **3**A may be referred to as gradiometers and/or magnetic quadrupoles and the loops in FIG. **3**B as gradiometers and/or octupoles, respectively. The quadrupole configuration may develop a voltage proportional to the magnetic field gradient in the left-to-right orientation. The 4-lobe configurations can be configured to measure field gradients (FIG. **3**B), and gradients of field gradients (FIG. **3**C). FIG. **3**D is representative of embodiments where multiple lobes may extend along a linear

dimension. In embodiments, higher-order multipoles with an even number of lobes can also be configured to measure spatial perturbations to the magnetic field. In embodiments, the lobes depicted in FIG. **3**A-**3**D may use multiple turns of conductor.

Each of these configurations can accomplish the goal of measuring magnetic field perturbations due to the presence of metallic FOD. The configurations with multiple lobes may have an advantage in covering more area without substantially reducing the likelihood of detecting FOD of similar characteristic size to the lobes.

The loop configurations depicted in FIG. **2** and FIG. **3**A-**3**D are depicted as circular to illustrate the direction of the induced current in the presence of an oscillating magnetic field. The plus and minus signs indicate whether the induced current flows mostly counter-clock-wise or clock-wise. Shapes other than circles may be better suited for arrays with high-area fill factor. Examples include squares, rectangles, hexagons, and other shapes that tile with little interstitial space in between them. FIG. **4**A shows an example of square-shaped coils where the array is assumed to extend further than shown and to have an equal number of plus and minus loops. The wires of the coils may be connected so that the induced currents flow in the directions indicated by the plus and minus signs.

For the configuration shown in FIG. **4**A a symmetrical piece of FOD can be placed in a position between adjacent loops so that the field perturbation may not generate a detectable magnetic field gradient. Such a "blind spot" is depicted in FIG. **4**A. In accordance with exemplary and non-limiting embodiments, a second layer of arrayed loops may be placed above a first layer and may be offset laterally as shown in FIG. **4**B. The offset may be chosen so that the "blind spots" of the first layer of sensors correspond to locations of maximum detectability for the second layer. In embodiments, the offset may be any offset than improves the likelihood of detection of the FOD relative to the single array detection probability. In this way, the likelihood may be reduced of having substantial blind spots where a piece of FOD may not be detectable. Similar schemes of one or more offset arrays can achieve roughly the same advantage in reducing blind spots. The orientations of the loops in multiple arrays may also be changed to handle non-uniform magnetic fields.

In embodiments the individual loops or lobes of the dipoles, quadrupoles, octupoles, and the like may be of multiple sizes or of nonuniform sizes. In embodiments where the gradiometer may cover areas of nonuniform magnetic field the loops may be sized to ensure a minimal voltage at the output of the gradiometer loops when no FOD is present. The loops may be sized such that a larger loop is positioned in an area of weaker magnetic field and the smaller loops are positioned in the areas of higher magnetic field. In embodiments the loops may be sized such that a larger loop is positioned in an area of more uniform magnetic field and a smaller loop is positioned in an area of less uniform magnetic field.

In accordance with exemplary and non-limiting embodiments, an array of FOD sensors may comprise multiple types of sensors. In embodiments, a FOD sensor may comprise single loop sensors and/or dipole gradiometers and/or quadrupole gradiometers and/or octupole gradiometers and so on. Some areas of the FOD sensor may comprise no gradiometers. A FOD sensor may comprise temperature sensors, organic material sensors, electric field sensors, magnetic field sensors, capacitive sensors, magnetic sensors, motion sensors, weight sensors, pressure sensors, water sensors, vibration sensors, optical sensors, and any combination of sensors.

Active FOD Detection Processing

The coil configurations described above (FIG. **2** to FIG. **4**) may develop an oscillating voltage in the presence of an oscillating magnetic field that is non-uniform because of, for example, the presence of FOD. In accordance with exemplary and non-limiting embodiments, a read-out amplifier connected to a given coil may have a high input impedance. This arrangement may prevent a substantial circulating current from developing in the sensor coil which could, in turn, spoil the Q-factor of the resonators used for wireless energy transfer. In embodiments, the loops, coils, gradiometers and the like may be connected to amplifiers and/or filters and/or analog-to-digital converters and/or operational amplifiers, and or any electronic component that may be arranged to have high input impedance. In embodiments, a FOD sensor may comprise a conducting loop and a high input impedance electronic component.

In accordance with exemplary and non-limiting embodiments, each conductor pair from each coil (loop, sensor, gradiometer) in an array may be connected to a readout amplifier and/or an analog-to-digital converter as shown in FIG. **5**. Each loop conductor **502** may be connected to an amplifier **506** and/or an analog-to-digital converter **508** and may produce an output **504** that may be used by other elements of a wireless energy transfer system or as an input to a processing element (not shown) such as a microprocessor to store and analyze the output of the coil, loop, sensor and/or gradiometer.

In other embodiments, the voltage on each coil in an array may be measured in sequence or may be multiplexed in a way that allows fewer read-out amplifiers or analog-to-digital converters to sample the array as shown in FIG. **6**. An array of loops of gradiometers **602**, **604**, **606** may be connected to a multiplexed amplifier **608** and connected to one or more digital-to-analog converters **610**. The output of the digital-to-analog converter **612** may be used by other elements of the wireless energy transfer system or as an input to a processing element (not shown) such as a microprocessor to store and analyze the output of the gradiometer.

In embodiments, each conductor pair of a sensor and/or gradiometer loop may be connected to active or passive filter circuitry to provide a high terminating impedance at very high or very low frequencies.

The voltage on a given coil may be sampled at increments that allow a processor to determine the amplitude and phase of the induced waveform relative to a reference waveform. In embodiments, the voltage on a given coil may be sampled at least twice per period of oscillation (i.e. at or above the Nyquist rate). In embodiments, the voltage on a given coil may be sampled less frequently (i.e. in higher-order Nyquist bands). The voltage waveform may be analog filtered or conditioned before sampling to improve the signal-to-noise ratio or to reduce harmonic content of the signals to be sampled. The voltage waveform may be digitally filtered or conditioned after sampling.

The time-sampled electrical signal from the FOD detector coils may be processed to determine the amplitude and phase with respect to a reference signal. The reference signal may be derived from the same clock used to excite the resonators used for wireless energy transfer.

In some embodiments the FOD detection system may include a separate frequency, field magnitude, and/or phase sampling loop **704** and electronics **702** to synchronize the

sensor and/or gradiometer readings to the oscillating magnetic fields of the wireless energy transfer system as shown in FIG. **7**.

In embodiments, the reference signal may be from a different oscillator at a different frequency.

An example of processing a figure-8 quadrupole configuration (FIG. **3**A) for FOD detection may be as follows:

1. With no FOD present, collect a time-sampled voltage waveform from one of the figure-8 loops
2. Compute the amplitude and phase of the fundamental frequency component (or of its harmonics)
3. Store the amplitude and phase as a baseline reference
4. With FOD present, collect a voltage waveform from the same figure-8 loop
5. Compute the amplitude and phase of the fundamental (or its harmonics)
6. Compare the amplitude and phase to the reference
7. On a polar plot (or in amplitude-and-phase space), if the distance between the signal and the reference exceeds a predetermined threshold, declare a detection of FOD.

In embodiments, the processing of the signal may be performed using analog electronic circuits, digital electronics or both. In embodiments, the signals from multiple sensors may be compared and processed. In embodiments, FOD sensors may reside on only one, or all, or some of the resonators in a wireless power transfer system. In embodiments, the signals from FOD sensors on different resonators may be processed to determine the presence of FOD and/or to give control information to the wireless power system. In embodiments, FOD detection may be controllably turned on and off. In embodiments, FOD detection and processing may be used to control the frequency of the wireless power transfer system, the power level transferred by the wireless power system, and/or the time period when wireless power transfer is enabled and/or disabled. In embodiments, the FOD detectors may be part of a reporting system that may report to a system user that FOD is present and/or that may report to higher level systems that FOD is present or is not present. In embodiments, a FOD detection system may comprise a "learning capability" that may be used to identify certain types of FOD and that may comprise system and/or system feedback to categorize types of FOD as harmless, in danger of heating, not allowed for other reasons, and the like.

In accordance with exemplary and non-limiting embodiments processing may be embedded into the FOD detection subsystem or data may be sent back to a central processor. The processing may compare collected voltage waveforms to reference waveforms and look for statistically significant changes. Those skilled in the art will understand that the waveforms can be compared in amplitude and phase, I or Q components, sine or cosine components, in the complex plane, and the like.

Exemplary Active FOD Detection Embodiments

Two specific and non-limiting embodiments of FOD detection systems that were fabricated are described below. Data have been collected from both embodiments that show them working as FOD detectors.

In the first embodiment a stranded wire was formed into a figure-8 loop forming a quadrupole as shown in FIG. **8** with a longer wire between the two loops (gradiometer **1**). The second embodiment was designed as shown as gradiometer **2** in FIG. **8**. The figure-8 loops were approximately 5 cm long. FIG. **9**A-**9**C show the voltage waveforms collected from the two sensors placed on top of a wireless energy source between the resonators for a 3.3-kW wireless energy transfer system, when the system was delivering 3.3 kW to a load. FIG. **9**A shows the small residual voltage (~30 mV_{rms}) on the two gradiometers pictured FIG. **8**. The residual voltage is due to a combination of non-uniform magnetic field, slight variations in lobe area, and electrical interference. Results from gradiometers #**1** and #**2** are plotted in as curve **904** and curve **902**, respectively. When a metallic chewing gum foil is placed on the right lobe of gradiometer #**2**, some flux is blocked and a substantial amplitude increase and slight phase shift is observable in FIG. **9**B, curve **902**. Conversely, when the foil is moved to the left lobe of gradiometer #**2**, the amplitude stays the same but the phase changes by 180° as shown in FIG. **9**C. These changes in phase and amplitude readings may be used to detect the presence of FOD on the sensors.

An embodiment of the figure-8 sensors was also fabricated using printed-circuit board (PCB) techniques to realize the sensor coils or loops. This embodiment may have advantages including low cost, higher fill factor (since the loops can be made into any shape and easily tiled using standard PCB processing techniques), higher uniformity, higher reproducibility, small size and the like. A higher-fill factor was obtained using tiled rectangular loops for a 16-channel array of single figure-8 sensors. The printed loops were highly uniform resulting in smaller (and flatter) baseline readings from the sensors when no FOD was present.

Other Embodiments

In embodiments the sensors and gradiometer sensors described above can be combined with other types of FOD sensors to improve detection likelihood and lower false alarms (system detects FOD when no FOD is present). For example, an array of temperature sensors can be integrated into the resonator assembly. If a piece of FOD begins to heat up it would disturb the normally expected spatial temperature distribution. That deviation can be used to send an alarm to the system controller. In embodiments, the temperature sensor may be used alone or in combination with a metal object sensor and/or it may be used as a backup or confirming sensor to the metallic object sensor.

Living beings such as pets can be difficult to detect. In general, they may not interact in a substantial manner with the magnetic field. In addition, living beings may not heat up appreciably when exposed to magnetic fields. Nonetheless, a wireless power system may need to shut down if living beings intrude into magnetic fields of certain field strengths. The field strength limits may be frequency dependent and may be based on regulatory limits, safety limits, standards limits, public perception limits, and the like. In embodiments, a dielectric sensor that measures changes in the fringe capacitance from a conductor such as a long wire can detect the proximity of living beings. In embodiments, this type of sensor may be used during diagnostic testing, prior to wireless energy transfer, and during wireless energy transfer.

Applications to Vehicle Charging

Detection of FOD may be an important safety precaution in many types of wireless energy transfer systems. For the example of a 3.3-kW car charging system, an example of an embodiment follows.

A block diagram of an exemplary EV Charger System is shown in FIG. **10**. The system may be partitioned into a Source Module and a Device Module. The Source Module may be part of a charging station and the Device module may be mounted onto an electric vehicle. Power is wirelessly transferred from the Source to the Device via the resonators. Closed loop control of the transmitted power

may be performed through an in-band and/or out-of-band RF communications link between the Source and Device Modules.

A FOD detector system (not shown) can be integrated into the system in a variety of places. In embodiments, FOD systems may be integrated into the Source Module, into the source resonator, into the housings or enclosures of the source resonator and the like. In other embodiments, the FOD systems may be integrated on the device side of the system. In other embodiments, FOD systems may be implemented on both the source and device sides of the wireless power transmission system. In embodiments, the FOD detection system may include multiple sensors and a processor with a discrimination algorithm. The processor can be connected to an interface that functions as an interlock in the Source control electronics. Other FOD detector systems may be connected to the charger systems through an additional interface or through an external interface. Local I/O at each module may provide interface for system level management and control functions in a wireless power system utilizing FOD detection.

The source resonator in a high power (3.3+kW) vehicle charging system may have its highest magnetic field density near the boundaries of the windings and, optionally, any magnetic material. In this area, an array comprising multiple channels of double-figure 8 coils with rectangular-shaped lobes can protect against inadvertent heating of metallic FOD. The array may be fabricated on a PCB and may have integrated filtering and signal conditioning included on the board. A second PCB of equivalent design may be positioned slightly above the first PCB and translated laterally in the manner described in FIG. **4**B. An algorithm like that described above may run in an on-board processor whose output may be transmitted to a system controller. The system controller can compare the output of the metallic FOD detector to the outputs of additional FOD detectors, such as those measuring temperature profiles or dielectric changes. The system can then decide whether to turn down or shut down the system if FOD is detected.

Some possible operation modes of a FOD detection system are as follows:

Low-power diagnostic tests can be performed without the vehicle present to check health and status of the charging station (infrequent) and to check for FOD prior to a vehicle driving over the source (more frequent).

After the vehicle arrives and is positioned over the source module, but prior to high-power charging, the FOD detector may verify that the source is still free of FOD.

During high-power charging the FOD detector can verify that no additional FOD has moved onto the coil.

While the invention has been described in connection with certain preferred embodiments, other embodiments will be understood by one of ordinary skill in the art and are intended to fall within the scope of this disclosure, which is to be interpreted in the broadest sense allowable by law. For example, designs, methods, configurations of components, etc. related to transmitting wireless power have been described above along with various specific applications and examples thereof. Those skilled in the art will appreciate where the designs, components, configurations or components described herein can be used in combination, or interchangeably, and that the above description does not limit such interchangeability or combination of components to only that which is described herein.

Note too, that the techniques described here may be applied to any wireless power system that transmits power using electromagnetic fields. In cases where we have described source and device resonators of highly resonant wireless power systems, one of skill in the art will understand that the same sensors, detectors, algorithms, subsystems and the like could be described for inductive systems using primary and secondary coils.

All documents referenced herein are hereby incorporated by reference.

What is claimed is:

1. A foreign object debris detection system for a wireless energy transfer system, comprising:

at least one magnetic field sensor comprising at least one magnetic field gradiometer; and

at least one readout circuit to measure electrical parameters of the at least one magnetic field sensor,

wherein the at least one magnetic field sensor is positioned within a magnetic field of the wireless energy transfer system.

2. The system of claim **1**, wherein the at least one magnetic field gradiometer comprises a figure-8 quadrupole conductor loop.

3. The system of claim **2**, wherein the figure-8 quadrupole conductor loop is printed on a circuit board.

4. The system of claim **3**, wherein the figure-8 quadrupole conductor loop is rectangular.

5. The system of claim **2**, wherein the system comprises an array of gradiometer loops positioned in the magnetic field of the wireless energy transfer system.

6. The system of claim **5**, wherein the system comprises multiple layers of offset and overlapped gradiometer loops.

7. The system of claim **1**, wherein the at least one magnetic field gradiometer comprises an octupole conductor loop.

8. The system of claim **1**, wherein the at least one readout circuit has an input impedance sufficient to substantially prevent circulating currents in the at least one magnetic field gradiometer.

9. The system of claim **8**, wherein the readout circuitry circuit is multiplexed among a plurality of gradiometer loops.

10. The system of claim **1**, wherein the at least one magnetic field gradiometer is at least twice a size of a smallest foreign object debris (FOD) to be detected.

11. A foreign object debris detection system for a wireless energy transfer system, comprising:

at least one magnetic field sensor;

at least one readout circuit to measure electrical parameters of the at least one magnetic field sensor; and

a feedback loop to adjust the parameters of the wireless energy transfer system based on readings from the foreign object debris detection system,

wherein the at least one magnetic field sensor is positioned within a magnetic field of the wireless energy transfer system.

12. A wireless energy transfer system with foreign object debris detection, the system comprising:

at least one wireless energy transfer source configured to generate an oscillating magnetic field;

at least one magnetic field gradiometer positioned in the oscillating magnetic field;

a readout circuit to measure electrical parameters of the field gradiometer; and

a feedback loop to control parameters of the wireless energy transfer source in response to the measured electrical parameters of the field gradiometer.

13. The system of claim **12**, further comprising at least one temperature sensor, wherein the at least one temperature

sensor is positioned to measure a temperature associated with the wireless energy transfer source.

14. The system of claim **12**, wherein a reading from the at least one magnetic field gradiometer is used to shut down the energy transfer of the at least one wireless energy transfer source.

15. The system of claim **12**, wherein the system further comprises an array of magnetic field gradiometers connected to high-input-impedance readout circuitry.

16. The system of claim **15**, wherein the high-input-impedance readout circuitry monitors a voltage signal of the magnetic field gradiometers.

17. The system of claim **16**, wherein the high-input-impedance readout circuitry monitors a phase of the voltage signal of the magnetic field gradiometers.

18. The system of claim **17**, further comprising a field sensing loop for synchronizing the readout circuit with a frequency of the oscillating magnetic field of the at least one wireless energy transfer source.

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