The power transmitter 201 has a power transmitter integrated circuit (IC) 2015 in communication with an off-chip controller 205. A signal generator in the form of a digitally controlled oscillator (DCO) and driver 207 are integrated onto the IC 2015. The output impedance of the signal generator 207 is variable by means of a dynamic impedance matching circuit 209 also integrated into the IC 2015 having an electrical signal amplitude detector in the form of feedback module 2029 and two capacitor banks 2011, 2013 in electrical connection with an off-chip inductor 2016 to which the electrode 200 is connected, which together determine the power transmitter output interface impedance, as will be explained below. The dynamic impedance matching circuit 209 includes a floating ground node 2051 of the transmitter forming an electrical signal return path to the transmitter 201 via parasitic capacitance 203 with the external ground. The forward transmission path formed by electrode 200 and the return transmission path 203 are therefore connected either side of the inductor 2016.

In this embodiment, the power receiver 301 comprises a power receiver integrated circuit (IC) 305 having a rectifier in the form of a bulk adaptation rectifier 307 and a DC-DC converter in the form of a dual-mode buck-boost converter 309 comprising a switch and pulse generator 3011 and a dual-mode Maximum Power Point Tracking module 3013. A signal electrode 300 is connected to the power receiver IC 305 via an input impedance circuit in the form of an off-chip detuned impedance booster circuit 3015 comprising a parallel L-C circuit. The impedance booster circuit 3015 includes a floating ground node 3051 of the receiver forming an electrical signal return path from the receiver 301 via parasitic capacitance 303 with the external ground. The forward transmission path formed by electrode 300 and the return transmission path 303 are therefore connected either side of the L-C circuit.

In the transmitting mode of the apparatus, an electrical signal is generated by the signal generator in the form of the DCO and Driver 207 and dynamic impedance matching at the environment interface is performed at the TX 201 by the output impedance circuit in the form of dynamic impedance matching circuit 209. At the RX 301 front-end, the detuned impedance booster (DIB) 3015 and the bulk adaptation rectifier (BAR) 307 are

implemented, to perform power recovery enhancement of the signal received via capacitive coupling via electrodes 200, 300. In the case of body-coupled energy harvesting (Fig. 2b), the DIB 3015 is disconnected, with the BAR 307 still in operation. In both power harvesting (Fig. 2b) and power transfer receiving mode (Fig. 2a) modes, the dual-mode buck-boost converter (DM-BBC) 309 performs maximum power point tracking and load regulation at 1.1 V, the nominal supply voltage for standard MOSFETS in 40 nm.

The detailed block diagram of the power transmitter 201 is shown in Fig. 4 with the resistive and capacitive components of environmental impedance resulting from connection with the body 105 represented schematically by resistor capacitor circuit 2023 and includes contributions from both the skin-electrode parasitic capacitance at the signal node 200, including a reflection coefficient, and the parasitic capacitance at the return path floating node 2051, both nodes being connected across the inductor 2016, as shown in Fig. 3. The digitally controlled oscillator (DCO) 2071 is arranged to generate a 40 MHz square wave, which outputs to a driver 2072 with an output impedance of 50 Ω. A dynamic impedance matching circuit 209 is arranged in between the driver 2072 output and the electrode 200 interface. The dynamic impedance matching circuit 209 has two capacitor banks 2011,2013 and an off-chip inductor 2016. Each capacitor bank 2011,2013 has eight capacitors 2027 arranged in parallel, each capacitor 2027 with a corresponding switch 2025 which enables the individual capacitors 2027 to be switched on or off to obtain different configurations of each capacitor bank 2011, 2013. The eight configurations of each capacitor bank 2011,2013 are controlled by the controller 205 arranged to output a control signal to the dynamic impedance matching circuit 209.

The first capacitor bank 2011 is arranged in series with the off-chip inductor 2016 and second capacitor bank 2013. The second capacitor bank 2013 is arranged in parallel with the off-chip inductor 2016. This arrangement enables the first capacitor bank 2011 to offer an adjustable capacitive element of the dynamic impedance matching circuit 209

and the second capacitor bank 2013 and the off-chip inductor 2016 to offer an adjustable inductive element for L-C impedance matching.

The transmitter further includes a ramp generator 2017, and envelope detector 2021, with outputs compared by comparator 2019 for input into the controller 205 which includes a digital clock. Together, the ramp generator 2017, and envelope detector 2021 and comparator 2019 make up the feedback module 2029 shown in Fig. 3.

In operation, dynamic matching of the environmental impedance (as represented by resistor-capacitor circuit 2023 in Fig. 4) is performed, which automatically configures the capacitor banks 2011, 2013. In conditions of matched impedance (where the driver 2072 output impedance equals the equivalent load impedance represented by 2023), half of the open-circuit voltage of the driver 2072 falls across the load. Therefore, an amplitude detector, in the form of an envelope detector (ED) 2021 (see N. M. Pletcher, S. Gambini and J. M. Rabaey, "A 2GHz 52 µW Wake-Up Receiver with -72dBm Sensitivity Using Uncertain-IF Architecture," IEEE International Solid-State Circuits Conference (ISSCC) Dig. Tech. Papers, vol. 51, pp. 524-633, Feb. 2008 for a detailed explanation) is used to track the output amplitude of the driver 2072 (which will be affected by the configuration of the capacitor banks 2011, 2013). The output amplitude of the driver 2017 is then compared using comparator 2019 with a ramp waveform generated by the ramp generator 2017 for voltage-time conversion using a digital counter in the controller 205. Such time information represented by the number of counting cycles provides feedback to the digital controller 205 and guides the capacitor bank 2011, 2013 reconfiguration direction, until the driver 2072 output amplitude eventually approaches the half-open circuit amplitude.

As explained above, the two capacitor banks 2011, 2013 have an 8-bit configurability with the least significant bit (LSB) controlling 50 fF resulting in 65,536 ($2^8 \times 2^8$) possible capacitor bank 2011, 2013 configurations being obtainable. The off-chip inductor 2016 is 2.2 µH. Area 501 of Fig. 5 illustrates the coverage obtainable by the dynamic matching network 209, with the corresponding expected environmental impedance range shown by area 503.

boosted RX 301 input impedance 903 is around the same level as the impedance of C_{RTN} 303 at the resonance/transmission frequency of 40 MHz.

The L-C circuit 801 is detuned for impedance matching across a wider range. Detuning is performed to achieve around 6-10X impedance boosting 903 across a 2.8 MHz bandwidth 905, which has been found to provide the best performance for a transmission frequency of 40MHz.

Fig. 10 illustrates the bulk adaptation rectifier ("BAR") 307. The BAR 307 has eight switches 5201-5208 which are arranged into two groups 5201-5204 and 5205-5208. 5201-5204 are arranged as a full-wave gate differential-drive cross-coupled rectifier with applied voltage V_{IP} 5209 – V_{IM} 5211 and output signal V_{RECT} 5213. Specifically, 5201 and 5202 are p-well transistors gated by V_{IM} 5211 and V_{IP} 5209 respectively with bulk connected towards V_{RECT} 5213 and 5203 and 5204 are deep n-well transistors gated by V_{IP} 5209 and V_{IM} 5211, respectively with bulk connected towards ground. Switches 5205-5208 are n-well transistors arranged to connect the bulk of switches 5201 to 5204 to the applied voltage V_{IP} 5209 - V_{IM} 5211. Specifically switches 5208,5205 are arranged to connect the bulk of switches 5203, 5202 respectively to V_{IP} 5209; and switches 5206,5207 and arranged to connect the bulk of switches 5204,5201 respectively towards V_{IM} 5211 The BAR 307 therefore has two modes of operation: switches 5205-5208 switched off ("non-bulk biased mode", or equivalently "normal mode") and switches 5205-5208 switched on ("bulk biasing mode").

Fig. 11 illustrates the operation of the BAR 307 in the two modes (certain reference numerals from Fig. 10 are omitted in Fig. 11 for conciseness). When the input amplitude drops below a threshold value, for example 0.4 V, the rectifier 307 is switched to a bulk biasing mode in which switches 5205-5208 are turned on as shown by configuration 1003, which connects the bulk of switches 5201-5204 towards V_{IP} 5209 and V_{IM} 5211, allowing their bulk voltages to alter dynamically based on the AC input. In configuration 1005, during the half-sine cycle where V_{IP} 5209 is higher than V_{IM} 5211, switches 5201, 5203 are in the forward conduction path and are forward bulk biased. Their threshold voltage is thus reduced, allowing more forward conduction current to V_{RECT} 5213. On the

309 comprises a switch matrix 1301, a pulse generation module 1303 and a controller in the form of a pulse width controller 1305, as well as control switch drivers 1307 and an adaptive level shifter (ALS) 1309.

The switch matrix 1301 has two p-well transistors 1311,1313 with an inductor 1319 connected in series between them and two n-well transistors 1315,1317 connecting either side of the inductor 1319 to ground. The gate voltage of transistor 1311 is controlled by control signals generated by the ALS 1309 with the gate voltage of transistors 1313-1317 controlled by control signals generated by the switch drivers 1307.

In operation, the switch matrix 1301 converts input voltage V_{IN} output by the rectifier 307 and converts it to V_{OUT} for supplying a device or storage. V_{OUT} is regulated to a constant 1.1V, which is the nominal supply voltage for standard MOSFETS in 40 nm.

The pulse generation module 1303 comprises Tuneable T1 (1325), T2 (1323) and T0 (1321) delay modules, each of which has a plurality of configurations, a fixed delay module 1327 and a NOR gate 1337 with the total delay from all modules 1325, 1323, 1321 and 1327 and an enabling signal $\overline{EN}$ 1335 as inputs, with $\overline{EN}$ 1335 held to 0 when half the output voltage V_{OUT} is below a reference voltage, as will be explained later.

In operation, the pulse generation module 1303 is arranged to output a signal PHI1 to both the ALS 1309 and switch drivers 1307 and the pulse width controller 1305 to output signal PHI2 to the switch drivers 1307 for control of the switch matrix 1301 and resulting in charging and discharging of the inductor 1319 according to switch 1311, 1313, 1315, 1317 configuration. Fig. 13b shows a schematic representation of the expected PHI1, PHI2 signals and resulting current I_L across the inductor 1319. PHI1 includes a pulse 1701 of duration T1 following a MPPT range settling period, or equivalently discontinuous mode (DCM) time 1703 of the converter 309, T0**.** PHI2 includes a pulse 1705 of duration T2 which occurs after T1. T1 and T2 correspond to the inductor 1319 charging and discharging time, respectively, as can be seen from the peak 1707 in the current $I_{L.}$

The configurations of the tuneable delay modules 1321 to 1325 are controlled by modules 1329, 1331, 1333 in the pulse width controller 1305, specifically Maximum

loss, with larger switches lead to higher switching loss but lower conduction loss, and vice versa.

Fig. 17c shows an outline of the method of determining T1 and T2. In step S5301, the T0 1703 configuration is selected using the mode selector 1333. In step S5303, an initial T1 configuration is selected. In S5305, the ZCS configuration of T2 is determined given the selected T0 1703 configuration and the T1 configuration. In S5307, the T1 configuration is altered to an adjacent configuration. The direction of adjustment of the T1 configuration is determined by the trend of change in the value of the inductor discharging time (T2) which represents the input power trend of change, as will be described below. The method then returns to step S5305.

Fig. 17d illustrates the method of asynchronous MPPT performed to determine T1, i.e. the method performed in step S5307 of Fig. 17c. Upon T2 being updated by ZCS in step S5305, the T2 register is updated in S1801 and the completion status of T2 adjustment under a given T1 is determined in S1803. If the T2 is settled, in step S1805 it is determined if the converter 309 is operating at the maximum frequency f_{SW}. If both of these requirements are met, in step S1807 the T1 register is updated, i.e. it is shifted by one bit in the direction determined in S5307, and in step S1809, the currently settled T2 is compared with the stored value and the T1 increment/decrement direction is determined and stored. If the T2 settled value is larger than the earlier settled value, T1 is incrementally adjusted in the same direction as in the previous adjustment. Otherwise, T1 adjusted in the opposite direction. At the very start of the process, T1 is incrementally increased, introducing perturbation for T2 change, which then affects the T1 direction later on. In step S1811 the current T2 value is stored, and in step S1813, the ZCS decision is stored, i.e. the incremental change in T2. After the method of Fig. 17d has been performed, a cycle check is performed and ‘T2 unsettled’ is assumed at the following cycle, should this be the first T2 value under the newly changed T1. At the steady state, the T1 configuration will oscillate in between two adjacent values which are upper and lower boundaries of the optimal value (yielding maximum power).

Claims

1. A power receiver, comprising:

(i) a first electrode arranged to be electrically coupled to a body of a living being, the first electrode operable to receive an electrical signal via the body; and

(ii) a rectifier for converting the received electrical signal into a rectified electrical signal, the rectifier having a plurality of rectifier switches and operable in a bulk biasing mode in which selected rectifier switches of the plurality of rectifier switches are forward bulk biased.

2. A power receiver according to claim 1, wherein the power receiver has an input load impedance; the power receiver further comprising an L-C circuit, the input load impedance being dependent on a resonance response of the L-C circuit.

3. A power receiver according to claim 2, wherein the L-C circuit comprises a parallel L-C circuit.

4. A power receiver comprising:

(i) a first electrode arranged to be electrically coupled to a body of a living being, the first electrode operable to receive an electrical signal via the body, the electrical signal having a power level;

(ii) a rectifier for converting the received electrical signal into a rectified electrical signal, the rectifier having a plurality of rectifier switches and operable in a bulk biasing mode in which selected rectifier switches of the plurality of rectifier switches are forward bulk biased;

(iii) a DC-DC converter for converting the rectified electrical signal to an output electrical signal, the DC-DC converter having a number of selectable discontinuous mode (DCM) times and operable between a power transmission operation mode in which the electrical signal is transmitted by

a power transmitter; and a power harvesting operation mode in which the electrical signal is harvested ambient energy, in dependence on the power level of the electrical signal; and

(iv) a controller arranged to select a discontinuous mode (DCM) time from the number of selectable discontinuous mode (DCM) times for the DC-DC converter in response to the operation mode of the DC-DC converter.

5. A power receiver, comprising:

(i) a first electrode arranged to be electrically coupled to a body of a living being, the first electrode operable to receive an electrical signal via the body, the electrical signal having a power level;

(ii) a rectifier for rectifying the electrical signal into a rectified electrical signal;

(iii) a DC-DC converter for converting the rectified electrical signal to an output electrical signal, the DC-DC converter having a number of selectable discontinuous mode (DCM) times and operable between a power transmission operation mode in which the electrical signal is transmitted by a power transmitter; and a power harvesting operation mode in which the electrical signal is harvested ambient energy, in dependence on the power level of the electrical signal; and

(iv) a controller arranged to select a discontinuous mode (DCM) time from the number of selectable discontinuous mode (DCM) times for the DC-DC converter in response to the operation mode of the DC-DC converter.

6. A power receiver according to claim 4 or claim 5, wherein the controller is arranged to select between a plurality of power transmission discontinuous mode (DCM) times in response to the power transmission operation mode, and between a plurality of power harvesting discontinuous mode (DCM) times in response to the power harvesting operation mode, in dependence of a voltage of the rectified electrical signal.

7. A power receiver according to any one of claims 4 to 6, wherein a switching frequency of the DC-DC converter in the power transmission operation mode is in the range 10 kHz to 500 kHz and a switching frequency of the DC-DC converter in the power harvesting operation mode is in the range 500 Hz to 6 kHz.

8. A power receiver according to any one of claims 4 to 7, wherein the controller is further arranged to adjust an inductor charging time of the DC-DC converter within a predetermined range until an input power of the DC-DC converter reaches a maximum value for the predetermined range.

9. A power receiver according to claim 8, wherein the controller is arranged to determine a direction of adjustment of the inductor charging time based on a corresponding inductor discharging time of the DC-DC converter.

10. A power receiver according to claim 8 or claim 9, wherein the inductor charging time of the DC-DC converter is between 100ns and 500ns.

11. A power receiver according to any one of the preceding claims, being formed as an integrated circuit (IC) chip.

12. A power receiver according to any one of the preceding claims, further comprising a floating ground node operable as a parasitic capacitive return path via an external ground for the electrical signal.

13. A power receiver according to any one of claims 1 to 11, wherein the first electrode comprises a receiving coil, the receiving coil being operable to receive the electrical signal via the body through magnetic resonance coupling with a transmitting coil.

14. A power receiver comprising:

(i) a first electrode arranged to be electrically coupled to a body of a living being, the first electrode operable to receive an electrical signal via the body;

(ii) a rectifier for converting the received electrical signal into a rectified electrical signal, the rectifier having a plurality of rectifier switches and

operable in a bulk biasing mode in which selected rectifier switches of the plurality of rectifier switches are forward bulk biased; and

(iii) a second electrode arranged to be electrically coupled to the body of the living being, wherein the electrical signal is galvanic current.

15. A power transmitter comprising:

(i) a signal generator having a variable output impedance; the signal generator operable to generate an electrical signal;

(ii) a first electrode arranged to be electrically coupled to a living being body for transmission of the electrical signal via the living being body;

(iii) an amplitude detector configured to measure an amplitude of the electrical signal;

(iv) a controller operable to adjust an impedance of the variable output impedance based on the amplitude of the electrical signal to enable the amplitude of the electrical signal to at least reach a threshold amplitude for transmission by the first electrode; and

(v) a second electrode arranged to be electrically coupled to the body of the living being, wherein the electrical signal is galvanic current.

16. Energy transfer apparatus, comprising:

(i) a power transmitter comprising: a signal generator operable to generate an electrical signal, and an electrode arranged to be electrically coupled to a living being body for transmission of the electrical signal via the living being body; and

(ii) a power receiver according to any one of claims 1 to 14.

17. Energy transfer apparatus according to claim 16, wherein the signal generator has an output load impedance, the power transmitter further comprising an L-C circuit, the output load impedance being dependent on a resonance response of the L-C circuit.

18. A method of receiving electrical power via an electrode coupled to a body of a living being, the method comprising:

receiving an electrical signal from the body via the electrode; and

rectifying the received electrical signal into a rectified electrical signal using a rectifier, the rectifier having a bulk biasing mode in which selected rectifier switches of a plurality of rectifier switches are forward bulk biased.

19. A method of receiving electrical power via an electrode coupled to the body of a living being according to claim 18, further comprising:

varying an input load impedance for receiving the electrical signal in accordance with a resonance response of an L-C circuit.

20. A method of receiving electrical power via an electrode coupled to the body of a living, the method comprising:

receiving an electrical signal from the body via the electrode;

rectifying the received electrical signal into a rectified electrical signal using a rectifier, the rectifier having a bulk biasing mode in which selected rectifier switches of a plurality of rectifier switches are forward bulk biased

measuring a power level of the electrical signal;

converting the rectified electrical signal to an output electrical signal using a DC-DC converter, the DC-DC converter having a number of selectable discontinuous mode (DCM) times and operable between a power transmission operation mode in which the electrical signal is transmitted by a power transmitter; and a power harvesting operation mode in which the electrical signal is harvested ambient energy, in dependence on the power level of the electrical signal; and

selecting a discontinuous mode (DCM) time from the number of selectable discontinuous mode (DCM) times for the DC-DC converter in response to the operation mode of the DC-DC converter.

21. A method of receiving electrical power via an electrode coupled to a body of a living being, the method comprising:

receiving an electrical signal from the body via the electrode;

measuring a power level of the electrical signal;

rectifying the electrical signal to obtain a rectified electrical signal;

converting the rectified electrical signal to an output electrical signal using a DC-DC converter, the DC-DC converter having a number of selectable discontinuous mode (DCM) times and operable between a power transmission operation mode in which the electrical signal is transmitted by a power transmitter; and a power harvesting operation mode in which the electrical signal is harvested ambient energy, in dependence on the power level of the electrical signal; and

selecting a discontinuous mode (DCM) time from the number of selectable discontinuous mode (DCM) times for the DC-DC converter in response to the operation mode of the DC-DC converter.

22. A method of receiving electrical power according to claim 20 or claim 21, further comprising: adjusting an inductor charging time of the DC-DC converter within a predetermined range to until an input voltage of the DC-DC converter reaches a maximum value for the predetermined range.

23. A method of receiving electrical power according to claim 22, further comprising:

determining an inductor discharging time of the DC-DC converter; and

determining a direction of adjustment of the inductor charging time, based on the inductor discharging time; and adjusting the inductor charging time of the DC-DC converter in the direction of adjustment.

24. A method of transferring power between a power transmitter and a power receiver; the power transmitter including a signal generator and a first transmitter electrode electrically coupled to a living being body; the power receiver including a rectifier and a first receiver electrode electrically coupled to the living being, the method comprising:

generating an electrical signal by the signal generator, the signal generator having an output impedance circuit, wherein an impedance of the output impedance circuit is adjusted based on one of resonance response of an L-C circuit, and an amplitude of the generated electrical signal;

transmitting the electrical signal via the first transmitter electrode to the living being body;

receiving the transmitted electrical signal, by the first receiver electrode, via the living being body;

rectifying the received electrical signal to produce a rectified electrical signal,

wherein the power transmitter further includes a second transmitter electrode coupled to the living being body, and the power receiver further includes a second receiver electrode, wherein the electrical signal being transmitted by the first transmitter electrode is galvanic current.