Wireless Charging Vibration Electric Toothbrushes

D/N: WAS-20A1EN

Introduction

Wireless charging vibration electric toothbrushes are divided into two parts, a wireless charging transmitter or charging base and a vibration electric toothbrush or toothbrush body. The charging base mainly includes two functions, wireless charging and ID identification. The toothbrush body includes four functions, wireless charging, lithium battery charging/discharging management, vibration motor control and LED indicators. The charging base is powered by a 5V USB interface and provides power to the toothbrush body through LC resonance, which provides a one-way communication function, so that the charging base can receive information and identify ID information returned by the toothbrush body. The toothbrush body provides charging over voltage protection and LED battery level display functions during the charging process.

The Holtek dedicated wireless charging MCU provides the required control signals mentioned above. This reference design will first introduce the operating principles of wireless charging and then explain each function control process step by step. This allows users to have an increased understanding of Holtek's wireless charging device usage.

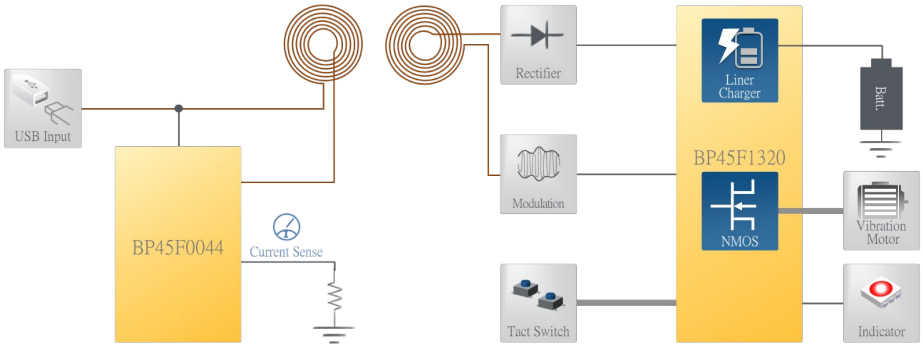

Figure 1. System Block Diagram

Application Areas

Wireless charging electric toothbrushes, wireless charging razors.

Solution Features

1. Few external components: includes an integrated demodulation circuit, an integrated high voltage NMOS circuit and a linear charging management circuit.
   - Charging base master MCU: includes an integrated demodulation circuit and a high voltage NMOS circuit.
     The BP45F0044 provides an integrated high voltage NMOS circuit to control LC resonance. An internal demodulation circuit together with an external current-sampling resistor can implement wireless signal demodulation. The I/O outputs have a 4-level programmable current function which can directly drive LEDs without the need for external components.
   - Toothbrush body master MCU: includes an integrated charging management circuit and a high voltage NMOS circuit.
     The toothbrush body master MCU, the BP45F1320 includes an integrated linear charging circuit which is used for lithium battery charging management. The device also includes a high voltage NMOS circuit which can directly drive DC motors to run. The I/O outputs have a 4-level programmable current function which can directly drive LEDs without the need for current limiting resistors.
2. Low power consumption: achieves power saving and automatic standby functions using ID identification.
   - Charging base: achieves power saving function using ID identification.
     An internal demodulation circuit together with an external current-sampling resistor can implement wireless signal demodulation. The ID returned by the toothbrush body is used to determine whether the charging base has been powered on to achieve to reduce power consumption.
   - Toothbrush body: The toothbrush will automatically enter the standby mode if there is no operation.
     When entering operating mode 1, the toothbrush body will automatically enter the sleep mode and the system will stop running. The average standby current is about 5μA to achieve to reduce power consumption.

Operating Principles

A wireless charging function is based on the principle of transmitting power from a charging base to a toothbrush body in the way of a fluctuating magnetic field, allowing the toothbrush body to sense an AC current. After the AC is sensed by the toothbrush body, it passes through a rectifier circuit, after which the DC current can be used by the MCU and for lithium battery charging. Communication also plays an important role in the wireless charging process. When a charging base has successfully communicated with a toothbrush, the charging base will then transmit power. When the power transmission function is not being used, the product enters the standby mode to reduce power consumption.

Functional Description

Solution Features

This reference design consists of a charging base and a toothbrush body. Their characteristics will be explained below.

Charging Base

- Operating voltage: DC 5V – powered by a USB interface.
- Operating current: 160mA – when connected to the toothbrush body.

The charging base is powered by a 5V USB interface. The LC resonance is implemented using a PWM function to control the internal MOS transistors. An internal demodulation circuit together with an external current-sampling resistor can implement communication demodulation. The ID returned by the toothbrush body is used to determine whether the charging base is powered on.

Toothbrush Body

- Operating voltage: DC 3.0V~4.2V – powered by a lithium battery.
- Operating current: Standby current consumption of 5μA (Operating Mode 1), operating current consumption of 400mA (LED + vibration motor).
- Lithium battery charging management: The master BP45F1320 MCU includes an integrated linear charging circuit which is used for lithium battery charging management.
- The high voltage NMOS circuit can directly drive the motor.

The toothbrush body is powered by an LC resonance circuit which is supplied to the MCU through a regulator circuit. The internal linear charging circuit is used for 3.7V lithium battery trickle charging, constant current and constant voltage charging control. The charging current varies according to the user design. During the charging process, the toothbrush body will communicate with the charging base, which will obtain the toothbrush body ID to implement the binding function.

Solution Functions

This reference design consists of a charging base and a toothbrush body. Figure 2 shows the product hardware. Figure 3 shows the main parts of the charging base. Figure 4 shows the main parts of the toothbrush body.

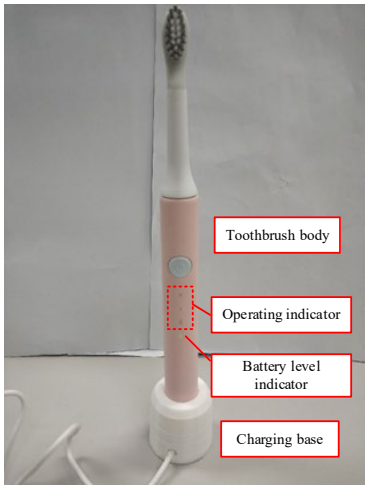

Figure 2. Prototype Product Hardware

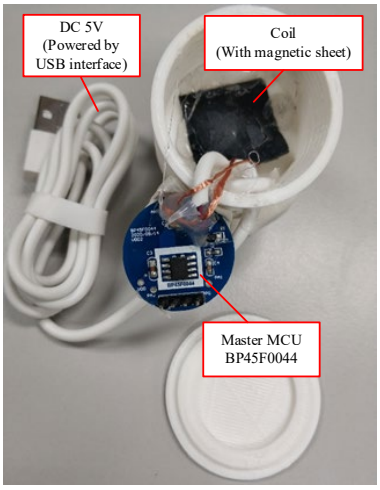

Figure 3. Charging Base Main Parts

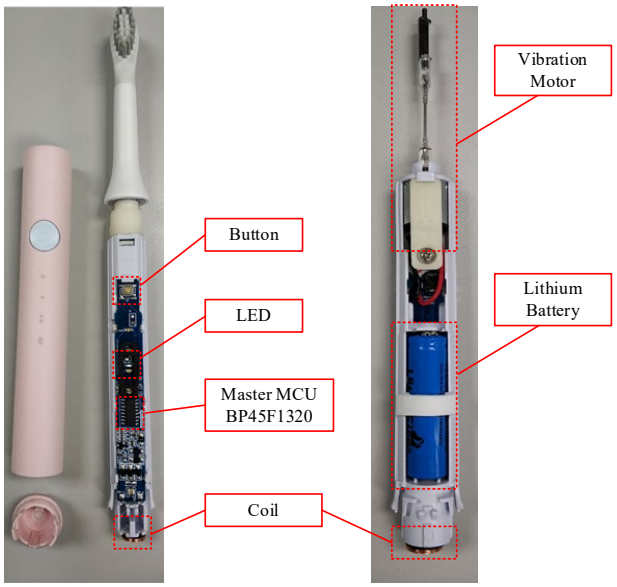

Figure 4. Toothbrush Body Main Parts

Charging Base

The charging base is powered by a 5V USB interface. The LC resonance is implemented using a PWM function to control the internal MOS transistors. An internal demodulation circuit together with an external current-sampling resistor can implement communication demodulation. The ID returned by the toothbrush body is used to determine whether the charging base is powered on.

Toothbrush Body

The toothbrush body is powered by an LC resonance circuit which is supplied to the MCU through a regulator circuit. The internal linear charging circuit is used for 3.7V lithium battery trickle, constant current and constant voltage charging control. The charging current varies according to the user design. During the charging process, the toothbrush body will communicate with charging base, which will obtain the toothbrush body ID to implement the binding function. Each mode is described below.

- Charging mode

  The toothbrush body will enter the charging mode when it has been placed on the charging base. During charging, when the battery voltage of the toothbrush body is less than 4.1V, the red LED indicator will flash. When the battery voltage is greater than 4.1V, the green LED indicator will flash. When the battery voltage is fully charged, the green LED indicator is always on.

- Operating modes

  The toothbrush body has four different operating modes, which can be cyclically switched by a button switch. In the operating mode 1, which is the Sleep mode, the motor and LEDs will turn off. In the operating mode 2/3/4, which represent continuous strong vibration/continuous weak vibration/continuous alternation between strong vibration and weak vibration respectively. Here three white LEDs indicate the current operating mode. When the battery voltage is greater than 3.5V, the green LED is always on. When the battery voltage is less than 3.3V, the red LED is always on. If the battery voltage falls between 3.3V and 3.5V, the last LED state will be maintained.

Operating Description

1. Toothbrush body: The toothbrush body is corresponded to the charging base, it cannot be charged when changing with the charging base. The toothbrush body also can be used to test the ID identification functions.
2. Button: A button switch is used to switch the operating modes.
3. Mode indicator: Display the operating modes.
4. Battery level indicator: Shows the battery level during the charging or discharging process.
5. Charging base: The charging base ID is consistent with the toothbrush body ID.

Solution Design Description

This reference design is composed of a charging base and a toothbrush body. The charging base uses the BP45F0044 as a master MCU and provides 0.5K of Flash Program Memory, 4 bidirectional I/Os, a high voltage NMOS, a programmable PWM circuit and a demodulation circuit. The toothbrush body uses the BP45F1320 as a master MCU and provides 1K of Flash Program Memory, 9 bidirectional I/Os, a high voltage NMOS and a programmable PWM circuit. In terms of wireless charging transmission and data reception, the charging base uses a BP45F0044 integrated high voltage NMOS and a programmable PWM circuit to control the LC resonance circuit to transmit wireless charging power. An integrated demodulation circuit is used to receive wireless charging data. For the vibration motor and lithium battery charging control, the toothbrush body uses a BP45F1320 integrated high voltage NMOS and a programmable PWM circuit to control the vibration motor and uses an integrated linear charging circuit for lithium battery charging management. The charging base and toothbrush body hardware will be introduced below.

Hardware Description

Charging Base Hardware Block Diagram

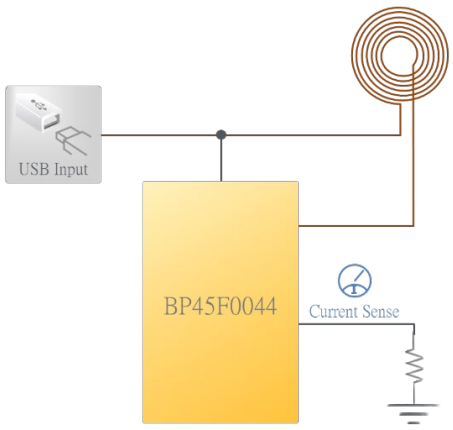

Figure 5. BP45F0044 Charging Base Hardware Block Diagram

- USB input

  The charging base is a 5V voltage system, which uses a high voltage NMOS transistor to control the LC resonance.

- Integrated demodulation circuit

  The current is converted to a voltage signal using an OCPI input pin and is amplified by an internal programmable operational amplifier PGA and is demodulated using the appropriate CMP settings and then finally used for communication.

Toothbrush Body Hardware Block Diagram

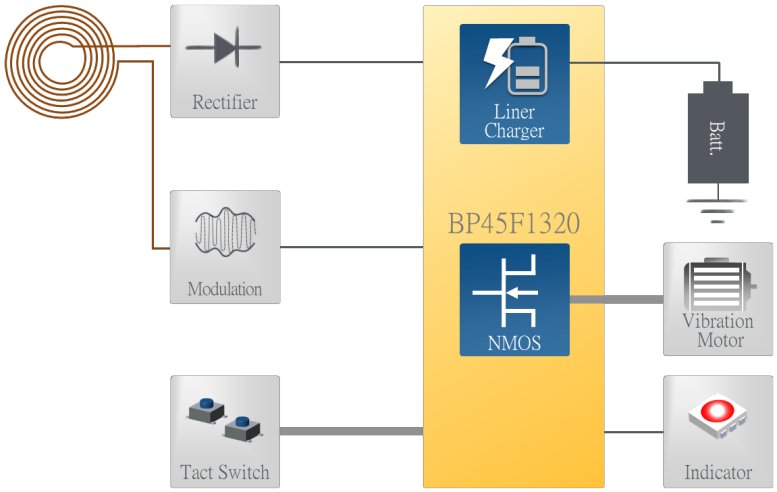

Figure 6. BP45F1320 Toothbrush Body Hardware Block Diagram

Power input: After receiving the LC resonance energy signal transmitted by the charging base, the toothbrush body will pass through a full-bridge rectifier circuit and a Zener regulator circuit, then provide power to the BP45F1320 linear charging circuit.

Linear charger circuit: Select trickle/constant current/constant voltage charging modes by detecting the battery voltage.

1. Trickle charging mode: During this initial charging process, for a battery that has been in an over-discharged state, when the battery voltage is less than 1.8V, the battery will be pre-charged at a constant current of 4mA. If the battery voltage is greater than 1.8V, the battery will be charged at 0.1 times a constant current charging current (I_{BAT_CC}) set by the firmware, that is, $0.1 \times I_{BAT\_CC}$.
2. Constant current charging mode: During this second stage, when the battery voltage is greater than 3V, the battery will be charged using a constant current charging current, which is controlled by the firmware.
3. Constant voltage charging mode: During this third stage, when the battery voltage is greater than 4.2V, it will be charged using a constant voltage. The charging current gradually decreases as the constant voltage charging time increases. When the charging current is less than 0.1 times the constant current charging current, then the charging will cease.

Note: Here a 300mAh capacity lithium battery is taken as an example, 0.1C means charging at 30mA and 1C means charging at 300mA.

- Modulation

  During the charging process, the toothbrush will carry out one-way communication with the charging base and transmits the ID code by the way of load change.

- High voltage NMOS

  The integrated high voltage NMOS and PWM circuit can directly drive vibration motor to run.

- Button

  A button switch is used to switch the operating modes.

- LEDs

  Three white LEDs are used to display the operating modes, a green LED and a red LED are used to display the battery charging and discharging state respectively.

Hardware Circuit Diagram

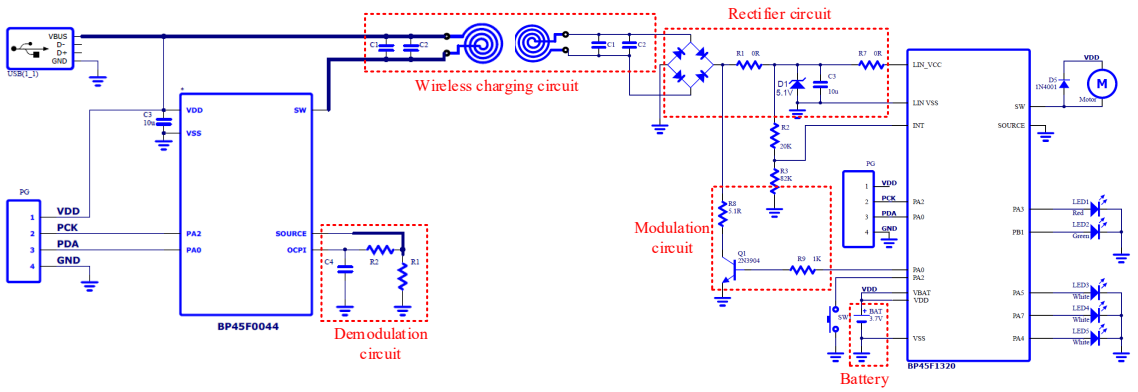

Figure 7. BP45F0044 and BP45F1320 Electric Toothbrush Solution Circuits

PCB Layout Front and Back Sides

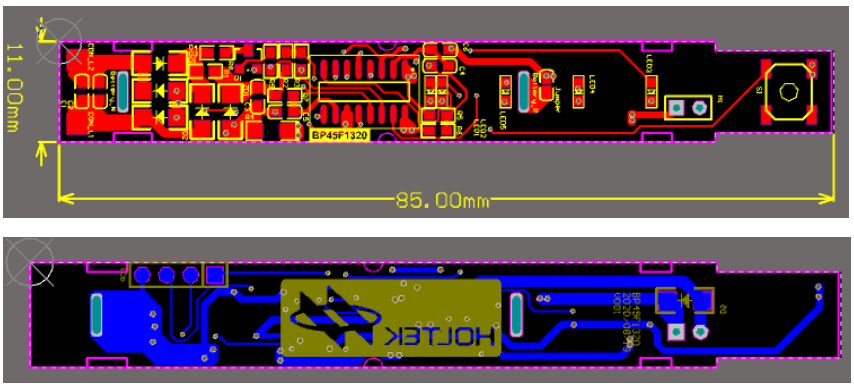

Figure 8. Toothbrush Body PCB Layout

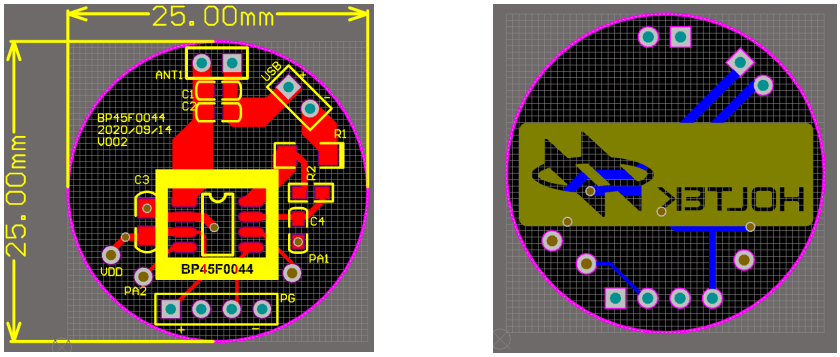

Figure 9. Charging Base PCB Layout

PCB BOM Table

Bill of Materials <Parameter Title not found>

Source Data From: SCH_Rx_BP45F1320-B01.SchDoc
Project: Free Documents
Variant: None

Creation Date: 2021/1/13 14:02:57
Print Date: 44209 44209.5855

Footprint	Comment	LibRef	Designator	Description	Quantity
	GND(1)	GND(1)		GND	10
	Induction(2)	Induction(2)	*?		1
CR2032	3.7V	Battery(1)	BAT	Battery	1
	15n	Cap(1)	C1	Capacitor	1
	3n	Cap(1)	C2	Capacitor	1
	10u	Cap(1)	C3	Capacitor	1
SOT-23	5.1V	Zener(1)	D1	Zener Diode	1
D1206	1N4001	DIODE_3	D5		1
D-38	Bridge	Bridge(1)	D?	Full Wave Diode Bridge	1
	BP45F1320	IC fat_1_1	IC1		1
LED-0	Red	LED(1)	LED1	Typical INFRARED GaAs LED	1
LED-0	Green	LED(1)	LED2	Typical INFRARED GaAs LED	1
LED-0	White	LED(1)	LED3, LED4, LED5	Typical INFRARED GaAs LED	3
	2.4V	Motor Servo(1)	Motor	Motor Servo	1
	CON fat	CON fat	PG		1
TO-226-AA	2N3904	NPN(1)	Q1	NPN Bipolar Transistor	1
	0R	Resistor(1)	R1, R7	Resisitor	2
	20K	Resistor(1)	R2	Resisitor	1
	82K	Resistor(1)	R3	Resisitor	1
	5.1R	Resistor(1)	R8	Resisitor	1
	1K	Resistor(1)	R9	Resisitor	1
	SW(2)	SW(2)	SW1	Switch	1
					34

Approved | Notes

Table 1. Toothbrush Body BOM

Bill of Materials <Parameter Title not found>

Source Data From: SCH_Tx_BP45F0044-A01.SchDoc
Project: Free Documents
Variant: None

Creation Date: 2020/5/25 04:07:41
Print Date: 43976 2020/5/25 16:19

Footprint	Comment	LibRef	Designator	Description	Quantity
HDR1X3		Inductor	ANT1	Inductor	1
0603C2		Cap	C1, C2, C4	Capacitor	3
0603C2	10u	Cap	C3	Capacitor	1
HDR1X4	ICP	Header 4	PG	Header, 4-Pin	1
1206	Res1	Res1	R1	Resistor	1
0603R2		Res1	R2	Resistor	1
NSOP 16PIN	BP45F0044	BP45V0044_1	U1		1
HDR1X2	Header 2	Header 2	USB	Header, 2-Pin	1
					10

Approved Notes

Table 2. Charging Base BOM

Coil Selection Description

- Charging base coil

  Inductance: 8.9μH

  Coil turns: 16, multi-core enameled wire

  Type: cylindrical, 0.95mm in height, 10mm in internal diameter, 20mm in external diameter, with magnetic sheet

  Wire diameter: 0.4mm

- Toothbrush body coil

  Inductance: 20μH

  Coil turns: 35, single-core enameled wire

  Type: cylindrical, 1.4mm in height, 5.9mm in internal diameter, 9.3mm in external diameter

  Wire diameter: 0.2mm

Charging Circuit Design Description

- Toothbrush body input power protection design

  Whether the lithium battery is fully charged or not, the charging base will both transmit the same energy to the toothbrush body through the resonance circuit. Therefore, it is required to design a front-end protection circuit. In order to prevent the toothbrush body MCU from being damaged due to too high an energy level, it is necessary to design a full-bridge rectifier circuit and a Zener diode at the front end.

  This reference design supports an operating current of about 45mA, an operating voltage of 5V and an operating power of 0.225W. Therefore a 0.5W Zener regulator is selected. Refer to the application note “Wireless Charging Over Voltage Application Solutions” for details (D/N: AN0532EN).

- Parallel resonance frequency design

  In this reference design, the charging base coil inductance is 8.9μH, the default resonance frequency is 130kHz, the resonance capacitance is 168.41nF which is calculated by the LC resonance formula. The LCFreq and PWMDuty parameters in the PWM program will be adjusted so that the PWM output can switch at the zero point of the LC resonance waveform. The PWM frequency adjusted by this reference design is 114.3kHz and the toothbrush body inductance is 20μH. Here the resonance capacitance of the toothbrush body is 96.97nF which is calculated based on the PWM frequency of the charging base. For detailed adjustment methods and notes, refer to the application note "Wireless Charging Transmission Power Adjustment and Design" (D/N: AN0558EN).

Communication Mechanism Design

The communication method for this reference design is based on load changes - changing load current. It will include a resistor at the toothbrush body VIN and use a transistor to control it. When the transistor is on, the load will increase and the charging base current will be larger. When the transistor is off, the load will decrease and the charging base current will be smaller. Changes in current will allow the charging base to receive these differences. The toothbrush body data signal will be decoded by circuits such as a back-end amplifier and comparator.

The corresponding settings should be prepared before the charging base communicates with the toothbrush body, that is, the ID code of the charging base and the toothbrush body must be the same. In the Holtek provided program, a fixed parameter of 2 bytes will be used as the ID code and 1 byte of data will be used as user-defined data.

When configuring the toothbrush body, the following parameters will be found in the main program.

1. c_ID_H: Toothbrush ID code - high byte - fixed parameter.
2. c_ID_L: Toothbrush ID code - low byte - fixed parameter.
3. a_Rx_STA: a user-defined variable for the toothbrush body.

The charging base provides users with a set of complete and convenient ID identification functions. It can also adjust the parameter settings such as the PWM operating time, Ping time interval and toothbrush body absence time. The toothbrush body has a user-defined 1 byte space for data transmission such as toothbrush body state, battery voltage, etc. The following section will describe the definable parameters.

1. c_ID_H: Charging base ID code - high byte - fixed parameter.
2. c_ID_L: Charging base ID code - low byte - fixed parameter.
3. c_PWM_ON_time: PWM Ping operating time, unit is 10ms.
4. c_ping_cycle: PWM Ping period (On + Off time), unit is 10ms.
5. c_time_out_after_success: The length of time after the toothbrush body is absent from the charging base, it returns to a Ping state, unit is 10ms.
6. c_OCPDA_offset: OCPDA offset calibration.

Refer to the application note "BP45F0044 Wireless Electric Toothbrush Application" for detailed design methods and notes (D/N: AN0569EN).

Software Usage Description

MCU Operating Environment

- BP45F0044

  V_{DD}: 5V

  Oscillator: 16MHz

  Watchdog Timer: 1s

  Timer: 50μs

- BP45F1320

  V_{DD}: 5V

  Oscillator: 8MHz

  Watchdog Timer: 0.25s

  Time Base: 1ms

Software Description

- BP45F0044

  ROM: 512×13 (use 458×13, percentage: 89%)

  RAM: 32×8 (use 27×8, percentage: 84%)

  OCP: demodulate with the appropriate debounce time when using the OCP for demodulation.

  PWM: set the appropriate frequency and period to control LC resonance.

  Timer: execute demodulation and timing once every 50μs when the flag is set.

- BP45F1320

  ROM: 1K×14 (use 967×14, percentage: 94%)

  RAM: 64×8 (use 60×8, percentage: 93%)

  INT: external voltage input interrupt, determine whether the toothbrush body is connected to the charging base.

  Time Base: execute timing and state debounce functions every 1ms.

  Linear Charging Circuit: set constant current charging and charging over voltage protection.

  ADC: read the battery voltage during discharging.

Charging Base Software Main Flowchart Description

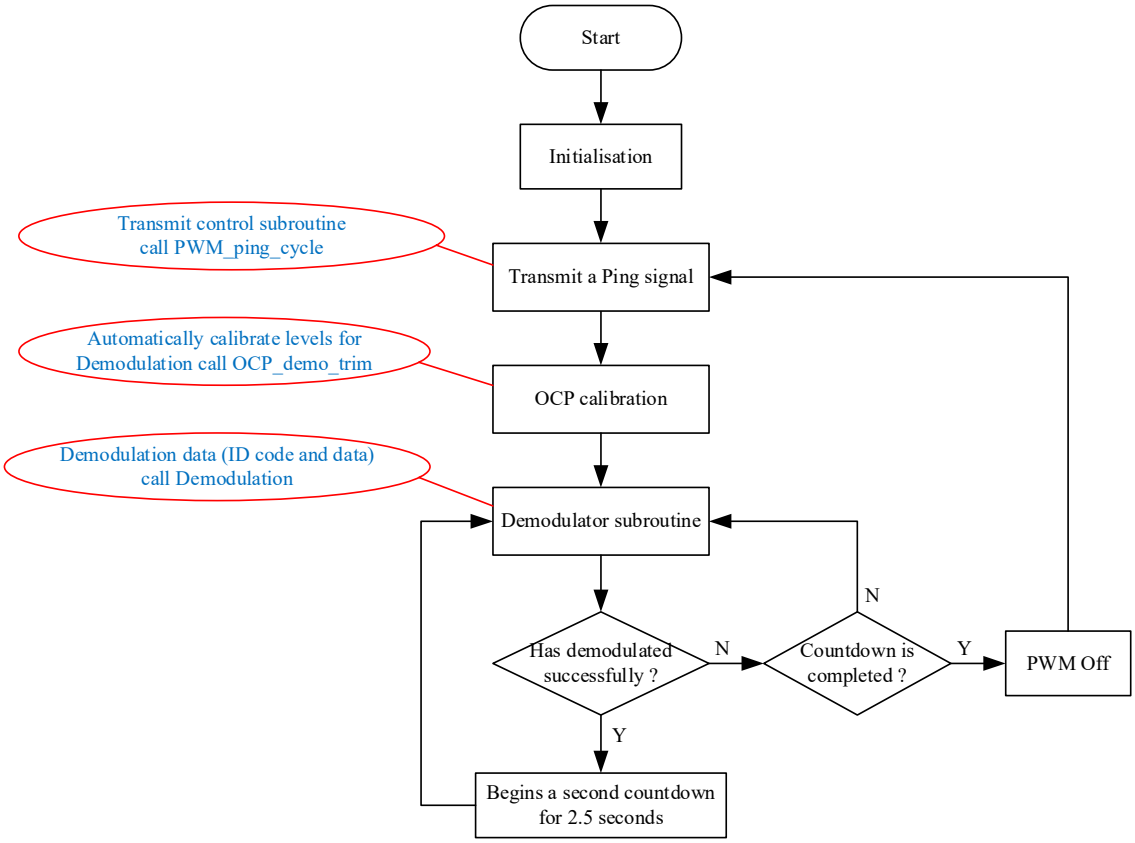

Figure 10. BP45F0044 Charging Base Main Flowchart

1. Initialisation: RAM clear, GPIO initialisation, Timer setting, WDT setting and ID code setting.
2. Transmit a Ping signal: The Ping signal is transmitted after a delay of 0.4 seconds.
3. OCP calibration: Automatic calibration at comparison points in the demodulation circuit.
4. Demodulation subroutine: Parsing ID code and data to determine whether the ID code is correct.
5. Demodulated successfully: When the demodulation is successful, reset the 2.5-second countdown timer. If this fails and the counter stops counting down, the PWM will be disabled.
6. Countdown has completed: The correct ID is required to be received within 2.5 seconds after a successful demodulation operation, otherwise the PWM will be disabled and the program will be executed again after 2.5 seconds.

Toothbrush Body Software Main Flowchart Description

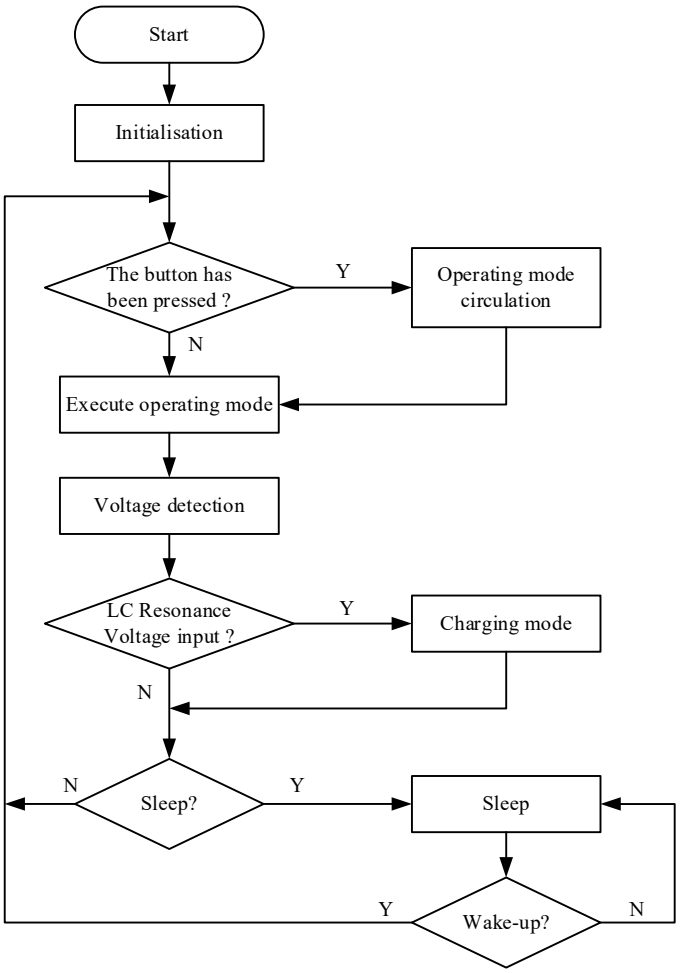

Figure 11. BP45F1320 Toothbrush Body Main Flowchart

1. Initialisation: RAM clear, GPIO initialisation, Timer setting and WDT setting.
2. Sleep: If the operating mode is not executed within 0.25 seconds, the MCU will enter the Sleep mode.
3. Wake-up: The MCU will be woken up by button pressed or LC resonance voltage input.
4. Operating mode circulation: It is increased by one each time when the operating mode is executed. When the operating mode is greater than five, the operating mode will be set as one.
5. Execute the operating mode: Refer to the toothbrush body operating mode execution subroutine description below.
6. Voltage detection: Measure the current battery voltage and then store the value into battery voltage register.
7. Charging mode: Refer to the toothbrush body charging mode subroutine description below.

Toothbrush Body Operating Mode Execution Subroutine Description

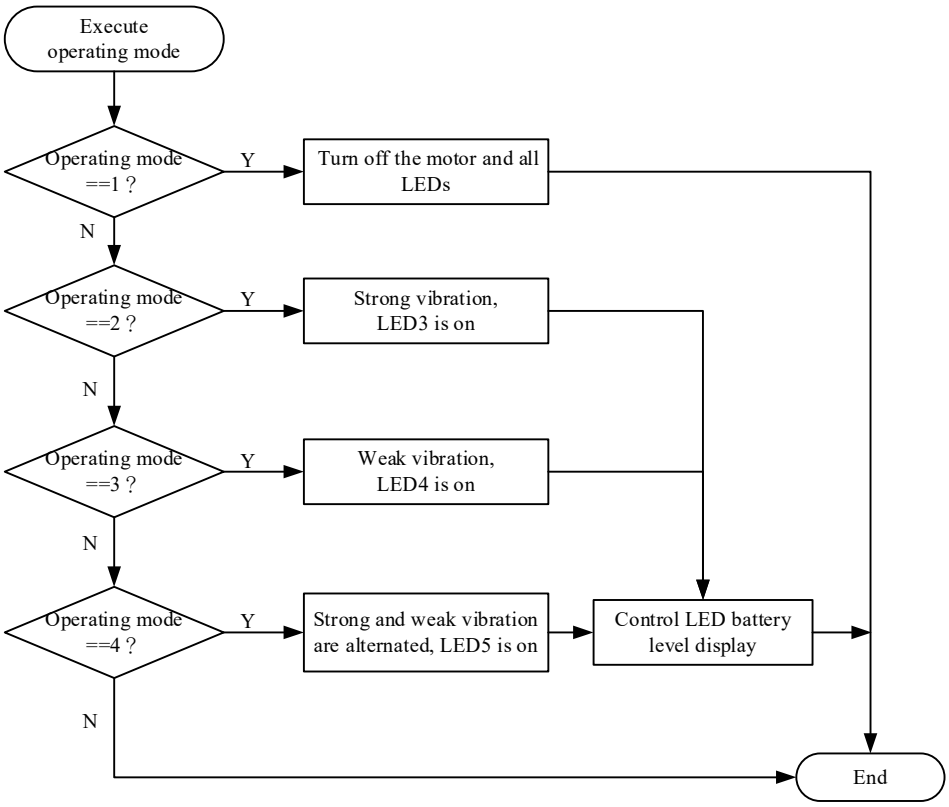

Figure 12. BP45F1320 Toothbrush Operating Flowchart

1. Operating mode: There are four operating modes for the toothbrush body. After the operating mode is executed, return to the main program immediately. Each operating mode is described below.
   - Operating mode 1: Turn off the vibration motor and all LEDs.
   - Operating mode 2: Continuous strong vibration, only white LED3 is always on.
   - Operating mode 3: Continuous weak vibration, only white LED4 is always on.
   - Operating mode 4: Continuous alternation between strong vibration and weak vibration, only white LED5 is always on.
2. Control LED battery level display: When the battery voltage is greater than 3.5V, the green LED is always on. When the battery voltage is less than 3.3V, the red LED is always on. If the battery voltage falls between 3.3V and 3.5V, the last LED state will be maintained.

Toothbrush Body Charging Mode Subroutine Description

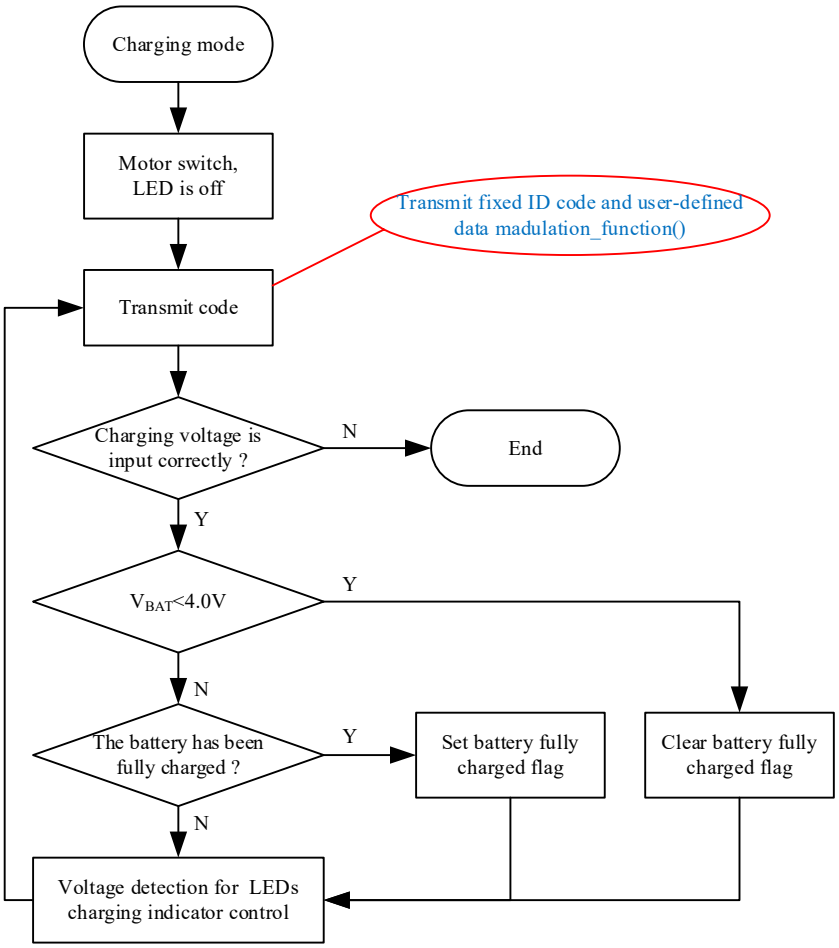

Figure 13. BP45F1320 Toothbrush Charging Flowchart

1. Turn off the vibration motor: disable the motor in the charging mode.
2. Whether the battery is fully charged: check the _VCCS and _CVS flags of the internal program to determine whether the battery is fully charged; If the battery is fully charged, the battery fully charged flag will be set; Otherwise, the battery fully charged flag will be cleared.
3. The charger voltage is input correctly: check the _VCCS flag of the internal program to determine whether the linear charger power input is compatible with the specification.
4. LEDs charging indicator control: the corresponding LEDs will be displayed according to the current battery voltage (V_{BAT}).
   - If the battery has been fully charged, the green LED2 is always on.
   - If the battery is not fully charged and the voltage is greater than 4.1V, the green LED2 will flash.
   - If the battery is not fully charged and the voltage is less than 4.1V, the red LED1 will flash.
5. V_{BAT}<4.0V: when the battery is fully charged, if the battery self-discharges to less than 4.0V, the battery fully charged flag will be cleared and the battery will be charged again.

Library Description

The following table lists each API used by the toothbrush body.

API Name	madulation_function()
API Function	Transmit toothbrush body ID and user-defined parameters
Input Parameters	a_ID_H: Toothbrush ID code - high byte a_ID_L: Toothbrush ID code - low byte a_Rx_STA: a user-defined parameter for the toothbrush body
Output Parameters	Null
Program Description	After this API is executed, a user-defined communication packet will be transmitted. Refer to the Communication Principle Description for the packet formats in detail.

The following table lists each API used by the charging base.

Command Name	Functional Description
Demodulation	Parse the communication data and confirm whether the toothbrush body ID is consistent with the charging base ID
OCP_demo_trim	Automatically calibrate the decoding level
PWM_ping_cycle	Transmit control subroutine
time_init	Timer initialisation
OCP_CAL	OCP comparator circuit offset calibration
DELAY_10us	10μs delay subroutine

The following table further describe each API used by the charging base.

API Name	Demodulation
API Function	Parse the communication data and confirm whether the toothbrush body ID is consistent with the charging base ID
Input Parameters	Null
Output Parameters	user_fg_demodu_ok will be 1 when the toothbrush body ID is consistent with the charging base ID
Program Description	After this API is executed, parse the communication data and confirm whether the toothbrush body ID is consistent with the charging base ID. user_fg_demodu_ok is set to 1 if the results match and 0 if not.

API Name	OCP_demo_trim
API Function	Automatically calibrate the decoding level
Input Parameters	Null
Output Parameters	Null
Program Description	After this API is executed, the decoding level will be automatically calibrated.

API Name	PWM_ping_cycle
API Function	Transmit control subroutine
Input Parameters	Null
Output Parameters	Null
Program Description	After this API is executed, it will determine whether to continue to enable wireless charging according to user_fg_demodu_ok and the delay time

API Name	time_init
API Function	Timer initialisation
Input Parameters	Null
Output Parameters	Null
Program Description	After this API is executed, the timer for transmission control will be initialised.

API Name	OCP_CAL
API Function	OCP comparator circuit offset calibration
Input Parameters	Null
Output Parameters	Null
Program Description	After this API is executed, the OCP comparator circuit offset will be calibrated

API Name	DELAY_10μs
API Function	10μs delay subroutine
Input Parameters	ACC
Output Parameters	Null
Program Description	After this API is executed, there is a delay of ACC×10 microseconds

Test Data

Test Item	V_{IN} (V)	I_{IN} (mA)	V_{OUT} (V)	I_{OUT} (mA)	Efficiency	Standby Current (Uncharged)
Measured Data	5	160	4.5	53	29.74%	5μA

Conclusion

This reference design has introduced how to use the BP45F0044 and BP45F1320 devices for wireless charging toothbrush prototype. It has also explained the operating principle and software control process of wireless charging toothbrushes. Based on the wireless charging toothbrush charging management, it is shown how ID recognition is implemented and the lithium battery is charged by the integrated linear battery charger using a constant current and constant voltage. The charging base includes an integrated demodulation circuit, which reduces the PCB size and the number of required peripheral components resulting in simplified product development.

Reference File

Reference file: BP45F0044 & BP45F1320 Datasheet.

For more information, consult the Holtek official website: www.holtek.com.

Revision and Modification Information

Data	Author	Issue
2021/01/27	林奕成	V1.00

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