

Demonstration System EPC9129 Quick Start Guide

*6.78 MHz, 33 W Class 4 Wireless Power System
using EPC8010/EPC2038/EPC2019/EPC2016C*

Revision 1.0



DESCRIPTION

The EPC9129 wireless power demonstration system is a high efficiency, AirFuel™ Alliance compatible, Zero Voltage Switching (ZVS), voltage mode class-D wireless power transfer demonstration kit capable of delivering up to 33 W into a transmit coil while operating at 6.78 MHz (Lowest ISM band). The purpose of this demonstration system is to simplify the evaluation process of wireless power technology using eGaN® FETs.

The EPC9129 wireless power system is comprised of the four boards (shown in figure 1), namely:

- 1) A Source Board (Transmitter or Power Amplifier) EPC9512
- 2) A Class 4 AirFuel compliant Source Coil (Transmit Coil)
- 3) A Category 3 AirFuel Alliance compliant Receive Device EPC9513
- 4) A Category 5 AirFuel Alliance compliant Receive Device EPC9514

The amplifier board (EPC9512) features the enhancement-mode, 100 V rated EPC8010 eGaN FET as the main power stage in a dual half bridge configuration; the 100 V rated EPC2038 eGaN FET used as the synchronous bootstrap FET, and the 200 V rated EPC2019 eGaN FET used in the SEPIC pre-regulator. The amplifier can be set to operate in either differential mode or single-ended mode and includes the gate driver(s), oscillator, and feedback controller for the pre-regulator that ensures operation for wireless power control based on the AirFuel standard. This allows for compliance testing to the AirFuel class 4 standard over a load range as high as $\pm 35j \Omega$.

The EPC9512 can operate in either single-ended or differential mode by changing a jumper setting. This allows for high efficiency operation with load impedance ranges suitable for single ended operation.

The circuits used to adjust the timing for the ZVS class-D amplifiers have been separated to further ensure highest possible efficiency setting. Each half bridge also includes separate ZVS tank circuits.

The amplifier is equipped with a pre-regulator controller that adjusts the voltage supplied to the ZVS class-D amplifier based on the limits of 3 parameters: coil current, DC power delivered to the ZVS class-D amplifier, and maximum operating voltage of the ZVS class-D amplifier. The coil current has the lowest priority followed by the power delivered and amplifier supply voltage having the highest priority. Changes in the device load power demand, physical placement of the device on the source coil and other factors, such as metal objects in proximity to the source coil, contribute to variations in coil current, DC power, and amplifier voltage requirements. Under any of these conditions, the controller will ensure the correct operating conditions for the ZVS class-D amplifier based on the AirFuel standard. The pre-regulator can be bypassed to allow testing with custom control hardware. The board

further allows easy access to critical measurement nodes for accurate power measurement instrumentation hookup. A simplified diagram of the amplifier board is given in figure 2.

The source and device coils are AirFuel compliant and have been pre-tuned to operate at 6.78 MHz with the EPC9512 amplifier. The source coil is AirFuel class 4 compliant and the device coils are AirFuel category 3 and category 5 compliant.

The EPC9513 (Category 3) device board includes a high frequency Schottky diode based full-bridge rectifier, DC smoothing capacitor and 5 V regulator. The regulator is based on a SEPIC converter that features a 200 V EPC2019 eGaN FET. The power circuit is attached to the backside of the coil which is provided with a ferrite shield that prevents the circuit from shunting the coil's magnetic field.

The EPC9514 (Category 5) device board includes a high frequency Schottky diode based full-bridge rectifier, DC smoothing capacitor and 19 V regulator. The regulator is based on a SEPIC converter that features a 100 V EPC2016C eGaN FET. The power circuit is attached to the side of the coil.

For more information on the EPC8010, EPC2038, EPC2019, or EPC2016C please refer to the datasheet available from EPC at www.epc-co.com. The datasheet should be read in conjunction with this quick start guide.

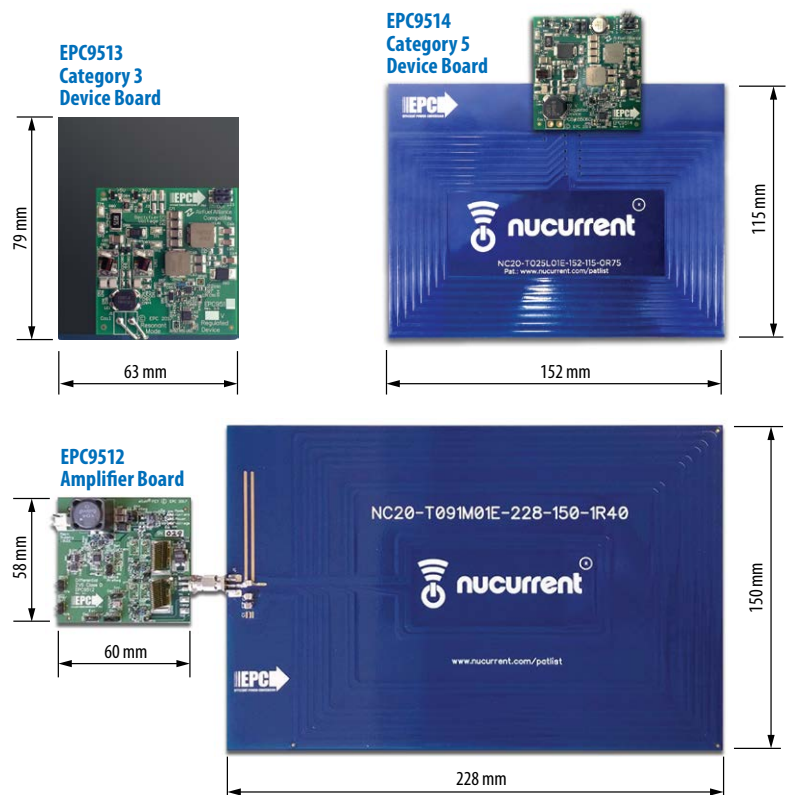


Figure 1: EPC9129 demonstration system.

Table 1: Performance Summary ($T_A = 25^\circ\text{C}$) EPC9512

Symbol	Parameter	Conditions	Min	Max	Units
V_{IN}	Bus Input Voltage Range – Pre-Regulator Mode	Also used in bypass mode for logic supply	17.4	24	V
V_{IN}	Amp Input Voltage Range – Bypass Mode		0	80	V
V_{OUT}	Switch-Node Output Voltage			80	V
I_{OUT}	Switch-Node Output Current (each)			1.8*	A
V_{extosc}	External Oscillator Input Threshold	Input 'Low'	-0.3	0.8	V
		Input 'High'	2.4	5	V
$V_{Pre_Disable}$	Pre-Regulator Disable Voltage Range	Floating	-0.3	5.5	V
$I_{Pre_Disable}$	Pre-Regulator Disable Current	Floating	-10	10	mA
$V_{Osc_Disable}$	Oscillator Disable Voltage Range	Open Drain/Collector	-0.3	5	V
$I_{Osc_Disable}$	Oscillator Disable Current	Open Drain/Collector	-25	25	mA
$V_{sgnDiff}$	Differential or Single-Select Voltage	Open Drain/Collector	-0.3	5.5	V
$I_{sgnDiff}$	Differential or Single-Select Current	Open Drain/Collector	-1	1	mA

* Maximum current depends on die temperature – actual maximum current will be subject to switching frequency, bus voltage and thermals.

Table 2a: Performance Summary ($T_A = 25^\circ\text{C}$) EPC9513 - Category 3 Device Board

Symbol	Parameter	Conditions	Min	Max	Units
V_{Unreg}	Un-regulated output voltage			38	V
I_{Unreg}	Un-regulated output current			1.5*	A
V_{Unreg_UVLOR}	UVLO Enable	Un-regulated voltage rising		10.96	V
V_{Unreg_UVLOF}	UVLO Disable	Un-regulated voltage falling	5.96		V
V_{OUT}	Output Voltage Range	$V_{Unreg_min} = 8.3\text{ V}$	4.8	5.1	V
I_{OUT}	Output Current Range	$V_{Unreg_min} = 8.3\text{ V}$	0	1*	A

* Actual maximum current subject to operation temperature limits.

Table 2b: Performance Summary ($T_A = 25^\circ\text{C}$) EPC9514

Symbol	Parameter	Conditions	Min	Max	Units
V_{Unreg}	Un-regulated output voltage		12.5	48	V
I_{Unreg}	Un-regulated output current			1.4*	A
V_{Unreg_UVLOR}	UVLO Enable	Un-regulated voltage rising		25	V
V_{Unreg_UVLOF}	UVLO Disable	Un-regulated voltage falling	12.5		V
V_{OUT}	Output Voltage Range	$V_{Unreg_min} = 8.3\text{ V}$	18.75	19.25	V
I_{OUT}	Output Current Range	$V_{Unreg_min} = 12.5\text{ V}$	0	1.4*	A

* Actual maximum current subject to operation temperature limits.

MECHANICAL ASSEMBLY

The assembly of the EPC9129 Wireless Demonstration kit is simple and shown in figure 1. The source coil and amplifier have been equipped with SMA connectors. The source coil is simply connected to the amplifier. The device board do not need to be mechanically attached to the source coil.

The coil sets of the EPC9111 and EPC9112 (both the source and device coils) are not compatible with the EPC9129 kit. To prevent inadvertent connection of either, the connectors of the amplifier and coils have been changed from reverse polarity to standard polarity. Please contact EPC for modifications to the original coil set to ensure compatibility with the EPC9512 amplifier.

It is recommended to insert a thin plastic insulator on top of the source coil to prevent accidental contact during operation when locating the device coils that can prevent damage to the amplifier.

DETAILED DESCRIPTION

The Amplifier Board (EPC9512)

Figure 2 shows the system block diagram of the EPC9512 ZVS class-D amplifier with pre-regulator and figure 3 shows the details of the ZVS class-D amplifier section. The pre-regulator is used to control the ZVS class-D wireless power amplifier based on three feedback parameters 1) the magnitude of the coil current indicated by the **green LED**, 2) the DC power drawn by the amplifier indicated by the **yellow LED** and 3) a maximum supply voltage to the amplifier indicated by the **red LED**. Only one parameter at any time is used to control the pre-regulator with the highest priority being the maximum voltage supplied to the amplifier followed by the power delivered to the amplifier and lastly the magnitude of the coil current. The maximum amplifier supply voltage is pre-set to 80 V and the maximum power drawn by the amplifier is pre-set to 33 W. The coil current magnitude is pre-set to $1.375\text{ A}_{\text{RMS}}$ but can be made adjustable using P25. The pre-regulator comprises a SEPIC converter that can operate at full power from 17.4 V through 24 V. If the system is operating in coil current limit mode, then the **green LED** will illuminate. For power limit mode, the **yellow LED** will illuminate. Finally, when the pre-regulator reaches maximum output voltage the **red LED** will illuminate indicating that the system is no longer able to operate to the AirFuel standard as the load impedance is too high for the amplifier to drive. When the load impedance is too high to reach power limit or voltage limit mode, then the current limit LED will illuminate incorrectly indicating current limit mode. This mode also falls outside the AirFuel standard and by measuring the amplifier supply voltage across TP1 and TP2 will show that it has nearly reached its maximum value limit.

The pre-regulator can be bypassed by connecting the positive supply directly to the ZVS class-D amplifier supply after removing the jumper at location JP1 and inserting the jumper into location JP50 to disable the pre-regulator followed by connecting the main positive supply to the bottom pin of JP1.

JP1 can also be removed and replaced with a DC ammeter to directly measure the current drawn by the amplifier. When doing this observe a low impedance connection to ensure continued stable operation of the controller. Together with the Kelvin voltage probes (TP1 and TP2) connected to the amplifier supply, an accurate measurement of the power drawn by the amplifier can be made.

The EPC9512 is also provided with a miniature high efficiency switch-mode 5 V supply to power the logic circuits on board such as the gate drivers and oscillator.

The amplifier comes with its own low supply current oscillator that is pre-programmed to $6.78\text{ MHz} \pm 678\text{ Hz}$. It can be disabled by placing a jumper into JP70 or can be externally shutdown using an externally controlled open collector / drain transistor on the terminals of JP70 (note which is the ground connection). The switch needs to be capable of sinking at least 25 mA. An external oscillator can be used instead of the internal oscillator when connected to J70 (note which pin is the ground connection) and the jumper (JP71) is removed.

The pre-regulator can also be disabled in a similar manner as the oscillator using JP50. However, note that this connection is floating with respect to the ground so removing the jumper for external connection requires a floating switch to correctly control this function. Refer to the datasheet of the controller IC and the schematic in this quick start guide for specific details.

The ZVS timing adjust circuits for the ZVS class-D amplifiers are each independently settable to ensure highest possible efficiency setting and includes separate ZVS tank circuits.

Additional protection features

An undervoltage-lockout circuit has been implemented for the input voltage (V_{IN}). The amplifier board will not start unless V_{IN} reaches its minimum required value specified in table 1.

A clamp diode also protects the board from V_{IN} over-voltage for a brief period and accidental reverse polarity connection with up to 11 A current protection.

On-Off-Key (OOK) modulation

On-Off-Key (OOK) modulation (as illustrated in figure 6) can be implemented by applying the modulation signal at J76. It is compatible with 5 V logic only. When the signal is high, the power stage functions normally; when the signal is low, the gate drive signal of one half-bridge is shut off. Therefore, for optimal performance, the signal should be synchronized with the oscillator signal. The modulation signal should also change state between the oscillator states and must complete an even number of clock cycles. Failure to follow this will lead to DC voltage shift on the ZVS capacitor (C_{ZVS}) and other harmonic generation issues in the amplifier output. The OOK modulation frequency will also become present and thus could lead to radiated emission violations if the frequency exceeds what is allowed in the ISM band.

When not using OOK modulation, J76 should be left open – an on-board pull-up resistor keeps the level high.

Single ended or Differential Mode operation

The EPC9512 amplifier can be operated in one of two modes; single-ended or differential mode. Single ended operation offers higher amplifier efficiency but reduced imaginary impedance drive capability. If the reflected impedance of the tuned coil load exceeds the capability of the amplifier to deliver the desired power, then the amplifier can be switched over to differential mode. In differential mode, the amplifier is capable of driving an impedance range of 1 Ω through 56 Ω and $\pm 35j \Omega$ and maintains either the 1.375 A_{RMS} coil current or deliver up to 33 W of power. The EPC9512 is set by default to differential mode and can be switched to single ended mode by inserting a jumper into J75. When inserted the amplifier operates in the single-ended mode. Using an external pull down with floating collector drain connection will have the same effect. The external transistor must be capable of sinking 25 mA and withstand at least 6 V.

For differential mode only operation, the two ZVS inductors L_{ZVS1} and L_{ZVS2} can be replaced by a single inductor L_{ZVS12} and by removing C_{ZVS1} and C_{ZVS2} .

ZVS Timing Adjustment

Setting the correct time to establish ZVS transitions is critical to achieving high efficiency with the EPC9512 amplifier. This can be done by selecting the values for R71, R72, R77, and R78 or P71, P72, P77, and P78 respectively. This procedure is best performed using a potentiometer installed at the appropriate locations that is used to determine the fixed resistor values. The procedure is the same for both single-ended and differential mode of operation. The timing MUST initially be set WITHOUT the source coil connected to the amplifier. The timing diagrams are given in figure 12 and should be referenced when following this procedure. Only perform these steps if changes have been made to the board as it is shipped preset. The steps are:

1. With power off, remove the jumper in JP1 and install it into JP50 to place the EPC9512 amplifier into Bypass mode. Connect the main input power supply (+) to JP1 (bottom pin for bypass mode) with ground connected to J1 ground (-) connection.
2. With power off, connect the control input power supply bus (19 V) to (+) connector (J1). Note the polarity of the supply connector.
3. Connect a LOW capacitance oscilloscope probe to the probe-hole of the half-bridge and the ground post.
4. Turn on the control supply – make sure the supply is approximately 19 V.
5. Turn on the main supply voltage starting at 0 V and increasing to the required predominant operating value (such as 24 V but NEVER exceed the absolute maximum voltage of 80 V).
6. While observing the oscilloscope adjust the applicable potentiometers to achieve the green waveform of figure 12.
7. Repeat for the other half-bridge.
8. Replace the potentiometers with fixed value resistors if required. Remove the jumper from JP50 and install it back into JP1 to revert the EPC9512 back to pre-regulator mode.

Determining component values for L_{ZVS}

The ZVS tank circuit is not operated at resonance, and only provides the necessary negative device current for self-commutation of the output voltage at turn off. The capacitors C_{ZVS1} and C_{ZVS2} are chosen to have a very small ripple voltage component and are typically around 1 μF . The amplifier supply voltage, switch-node transition time will determine the value of inductance for L_{ZVSx} which needs to be sufficient to maintain ZVS operation over the DC device load resistance range and coupling between the device and source coil range and can be calculated using the following equation:

$$L_{ZVS} = \frac{\Delta t_{vt}}{8 \cdot f_{sw} \cdot (C_{OSSQ} + C_{well})} \quad (1)$$

Where:

Δt_{vt} = Voltage Transition Time [s]

f_{sw} = Operating Frequency [Hz]

C_{OSSQ} = Charge Equivalent Device Output Capacitance [F]

C_{well} = Gate driver well capacitance [F]. Use 20 pF for the LM5113

NOTE. The amplifier supply voltage V_{AMP} is absent from the equation as it is accounted for by the voltage transition time. The C_{OSS} of the EPC8010 eGaN FETs is on the same order of magnitude as the gate driver well capacitance C_{well} which as a result must now be included in the ZVS timing calculation. The charge equivalent capacitance of the eGaN FETs can be determined using the following equation:

$$C_{OSSQ} = \frac{I}{V_{AMP}} \cdot \int_0^{V_{AMP}} C_{OSS}(v) \cdot dv \quad (2)$$

To add additional immunity margin for shifts in coil impedance, the value of L_{ZVS} can be decreased to increase the current at turn off of the devices (which will increase device losses). Typical voltage transition times range from 2 ns through 8 ns. For the differential case the voltage and charge (C_{OSSQ}) are doubled when calculating the ZVS inductance.

The Source Coil

Figure 4 shows the schematic for the source coil which is Class 4 AirFuel compliant. The matching network includes only series tuning. The matching network series tuning is differential to allow balanced connection and voltage reduction for the capacitors.

The Device Boards

Figure 5 shows the basic schematic diagram of the EPC9513 and EPC9514 device boards which comprises a tuning circuit for the device coil with a common-mode choke for EMI suppression, a high frequency rectifier and SEPIC converter based output regulator. The EPC9513 is powered using a Category 3 AirFuel Alliance compliant device coil and the EPC9514 is powered using a Category 5 AirFuel Alliance compliant device coil Both are by default tuned to 6.78 MHz for the specific coil provided with it. The tuning circuit comprises both parallel and series tuning which is also differential to allow balanced connection and voltage reduction for the capacitors.

The device boards have limited over-voltage protection using a TVS diode that clamps the un-regulated voltage to 38 V (EPC9513) or 46 V (EPC9514). This can occur when the receive coil is placed above a high power transmitter with insufficient distance to the transmit coil and there is little or no load connected. During an over-voltage event, the TVS diode will dissipate a large amount of power and the red LED will illuminate indicating an over-voltage. The receiver should be removed from the transmitter as soon as possible to prevent the TVS diode from over-heating.

The EPC9513 and EPC9514 can be operated with or without the regulator. The regulator can be disabled by inserting a jumper into position JP50 and connecting the load to the unregulated output terminals. In regulated mode, the design of the EPC9513 and EPC9514 controller will ensure stable operation in a wireless power system. The regulator operates at 280 kHz (EPC9513) or 300 kHz (EPC9514) and the controller features over current protection that limits the load current to 1 A for the EPC9513 and 2 A for the EPC9514.

The EPC9513 and EPC9514 device boards come equipped with Kelvin connections for easy and accurate measurement of the un-regulated and regulated output voltages. The rectified voltage current can also

be measured using the included shunt resistor. In addition, the EPC9513 and EPC9514 have been provided with a switch-node measurement connection for low inductance connection to an oscilloscope probe to yield reliable waveforms.

The EPC9513 is designed to operate in conjunction with EPC9127 (10 W EPC9510), EPC9128 (16 W EPC9509), EPC9129 (33 W EPC9512) and EPC9121 (10 W EPC9511) transmitter units. The EPC9514 is designed to operate in conjunction with EPC9129 (33 W EPC9512) transmitter units.

QUICK START PROCEDURE

The EPC9129 demonstration system is easy to set up and evaluate the performance of the eGaN FET in a wireless power transfer application. Refer to figure 1 to assemble the system and figures 8, 9, and 10 for proper connection and measurement setup before following the testing procedures.

The EPC9512 can be operated using any one of two alternative methods:

- Using the pre-regulator
- Bypassing the pre-regulator

a. Operation using the pre-regulator

The pre-regulator is used to supply power to the amplifier in this mode and will limit the coil current, power delivered or maximum supply voltage to the amplifier based on the pre-determined settings.

The main 19 V supply must be capable of delivering 2.3 ADC. **DO NOT turn up the voltage of this supply when instructed to power up the board, instead simply turn on the supply.** The EPC9512 board includes a pre-regulator to ensure proper operation of the board including start up.

- Make sure the entire system is fully assembled prior to making electrical connections and make sure jumper JP1 is installed. Also make sure the source coil and device coil with load are connected.
- With power off, connect the main input power supply bus to J1 as shown in figure 8. Note the polarity of the supply connector.
- Make sure all instrumentation is connected to the system.
- Turn on the main supply voltage to the required value (19 V).
- Once operation has been confirmed, observe the output voltage and other parameters on both the amplifier and device boards.
- For shutdown, please follow steps in the reverse order.

b. Operation bypassing the pre-regulator

In this mode, the pre-regulator is bypassed and the main power is connected directly to the amplifier. This allows the amplifier to be operated using an external regulator.

Note: In this mode there is no protection for ensuring the correct operating conditions for the eGaN FETs.

When in bypass mode it is crucial to slowly turn up the supply voltage starting at 0 V. Note that in bypass mode you will be using two supplies; one for logic and the other for the amplifier power.

- Make sure the entire system is fully assembled prior to making electrical connections and make sure jumper JP1 has been removed and installed in JP50 to disable the pre-regulator and to place the EPC9512 amplifier in bypass mode. Also make sure the source coil and device coil with load are connected.

2. With power off, connect the main input power supply bus $+V_{IN}$ to the bottom pin of JP1 and the ground to the ground connection J1 as shown in figure 8.
3. With power off, connect the control input power supply bus to J1. Note the polarity of the supply connector. This is used to power the gate drivers and logic circuits.
4. Make sure all instrumentation is connected to the system.
5. Turn on the control supply – make sure the supply is 19V range.
6. Turn on the main supply voltage to the required value (it is recommended to start at 0V and do not exceed the absolute maximum voltage of 80V).
7. Once operation has been confirmed, adjust the main supply voltage within the operating range and observe the output voltage, efficiency and other parameters on both the amplifier and device boards.
8. For shutdown, please follow steps in the reverse order. Start by reducing the main supply voltage to 0V followed by steps 6 through 2.

NOTE.

1. When measuring the high frequency content switch-node (Source Coil Voltage), care must be taken to avoid long ground leads. An oscilloscope probe connection (preferred method) has been built into the board to simplify the measurement of the Source Coil Voltage (shown in figure 11).
2. AVOID using a Lab Benchtop programmable DC as the load for the category 3 and category 5 device boards. These loads have low control bandwidth and will cause the EPC9129 system to oscillate at a low frequency and may lead to failure. It is recommended to use a fixed low inductance resistor as an initial load. Once a design matures, a post regulator, such as a Buck converter, can be used.

Go to www.epc-co.com periodically for updates on new wireless power device demonstration boards capable of delivering a regulated output.

THERMAL CONSIDERATIONS

The EPC9129 demonstration system showcases the EPC8010, EPC2019, EPC2038, and EPC2016C in a wireless energy transfer application. Although the electrical performance surpasses that of traditional silicon devices, their relatively smaller size does magnify the thermal management requirements. The operator must observe the temperature of the gate driver and eGaN FETs to ensure that both are operating within the thermal limits as per the datasheets.

NOTE. The EPC9129 demonstration system has limited current and thermal protection only when operating off the Pre-Regulator. When bypassing the pre-regulator there is no current or thermal protection on board and care must be exercised not to over-current or over-temperature the devices. Excessively wide coil coupling and load range variations can lead to increased losses in the devices.

Pre-Cautions

The EPC9129 demonstration system has no enhanced protection systems and therefore should be operated with caution. Some specific precautions are:

1. Never operate the EPC9129 system with a device board that is AirFuel compliant as this system does not communicate with the device to correctly setup the required operating conditions and doing so can lead to failure of the device board. Please contact EPC should operating the system with an AirFuel compliant device be required to obtain instructions on how to do this. Please contact EPC at info@epc-co.com should the tuning of the coil be required to suit specific conditions so that it can be correctly adjusted for use with the ZVS class-D amplifier.
2. There is no heat-sink on the devices and during experimental evaluation it is possible present conditions to the amplifier that may cause the devices to overheat. Always check operating conditions and monitor the temperature of the EPC devices using an IR camera.
3. Never connect the EPC9129 amplifier board into your VNA in an attempt to measure the output impedance of the amplifier. Doing so will severely damage the VNA.

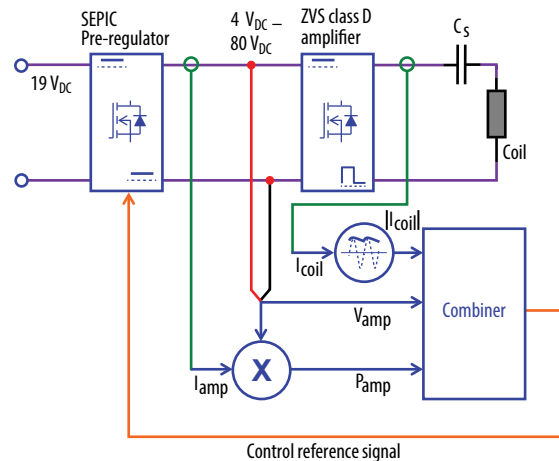


Figure 2: Block diagram of the EPC9129 wireless power amplifier.

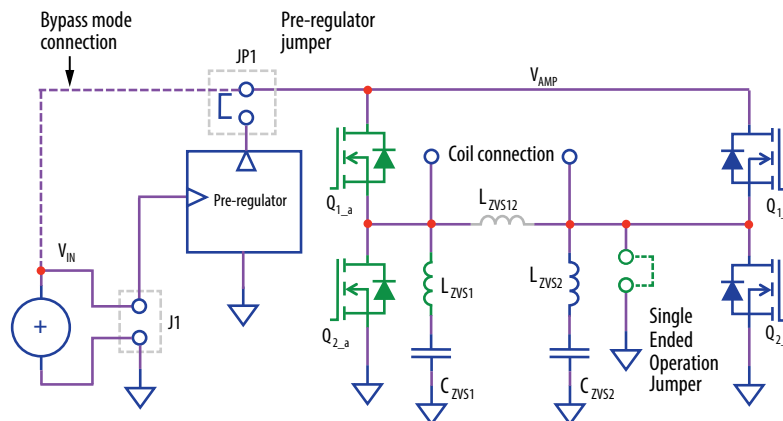


Figure 3: Diagram of EPC9129 ZVS class-D amplifier circuit.

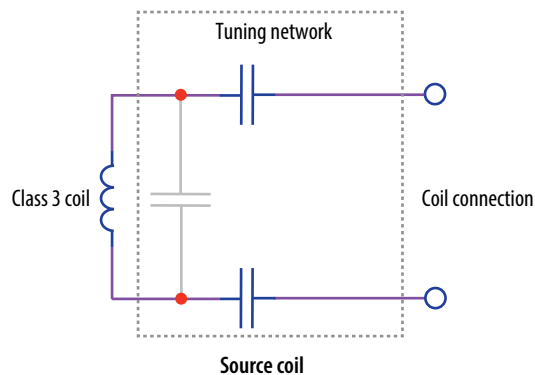


Figure 4: Schematic of AirFuel Class 4 source coil.

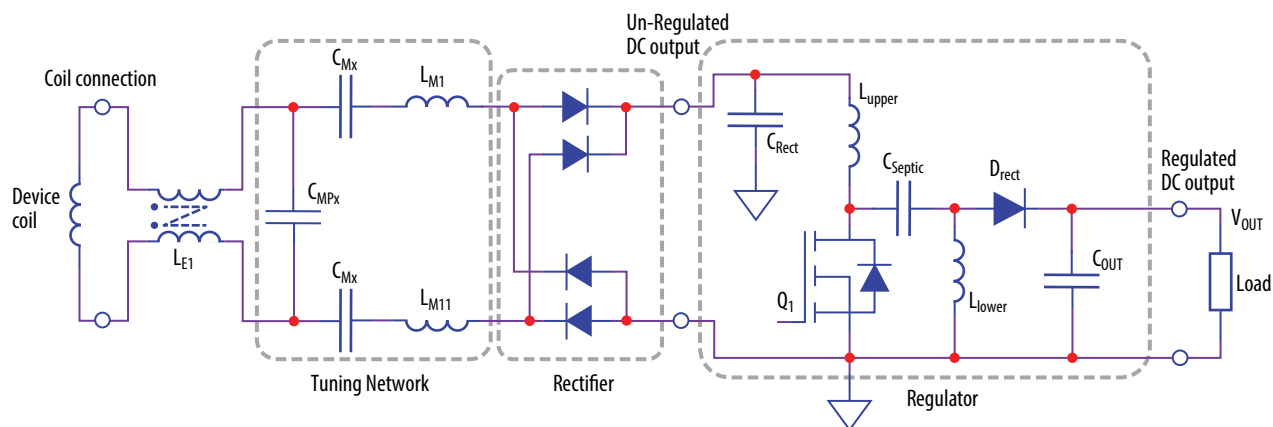


Figure 5: Schematic diagram of the EPC9513 and EPC9514 demo board.

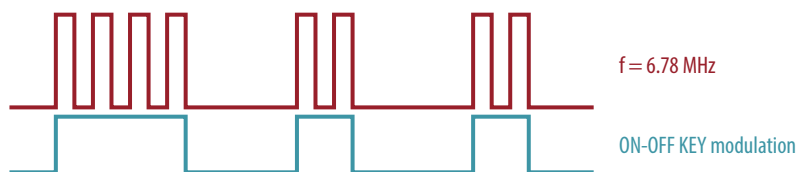


Figure 6: ON-OFF-KEY modulation.

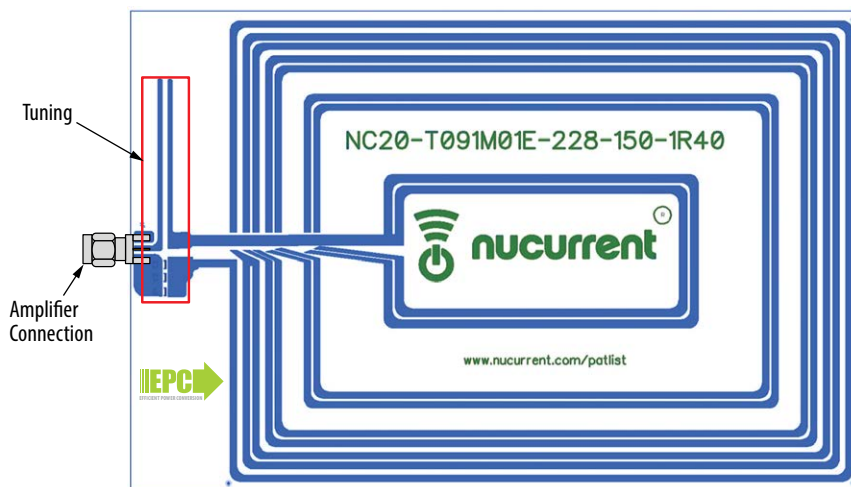


Figure 7: Proper connection for the source coil.

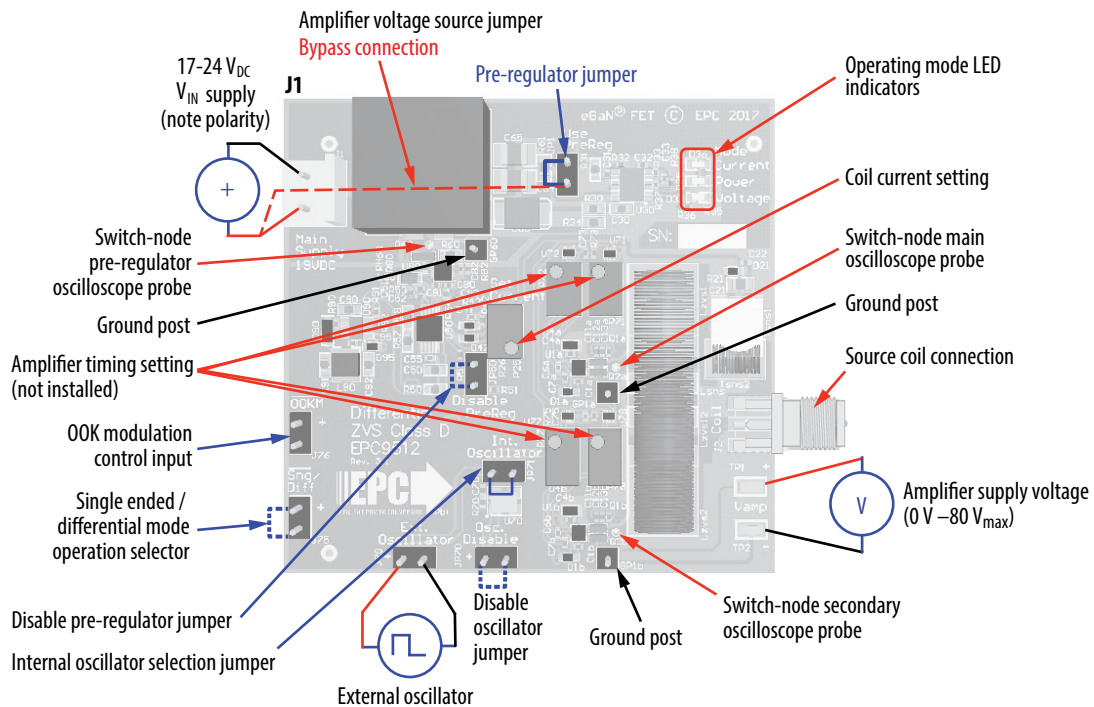


Figure 8: Proper connection and measurement setup for the amplifier board.

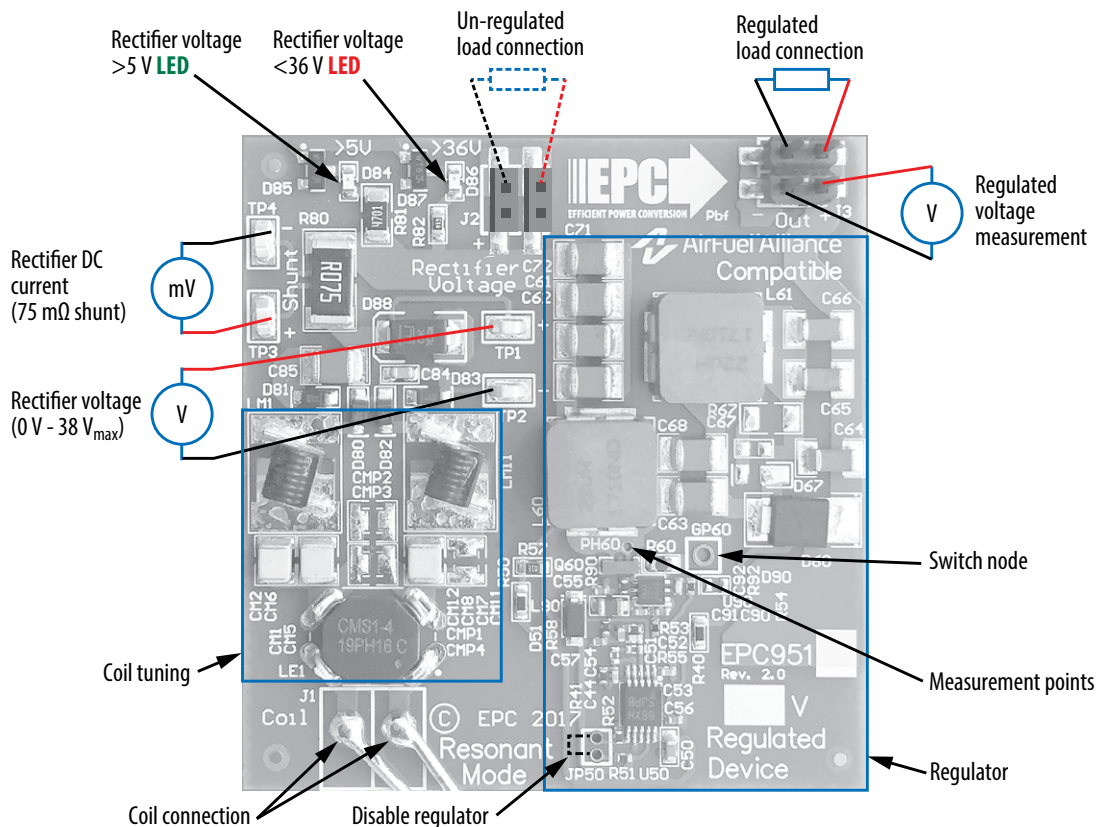


Figure 9: Proper connection and measurement for the EPC9513 receiver board.

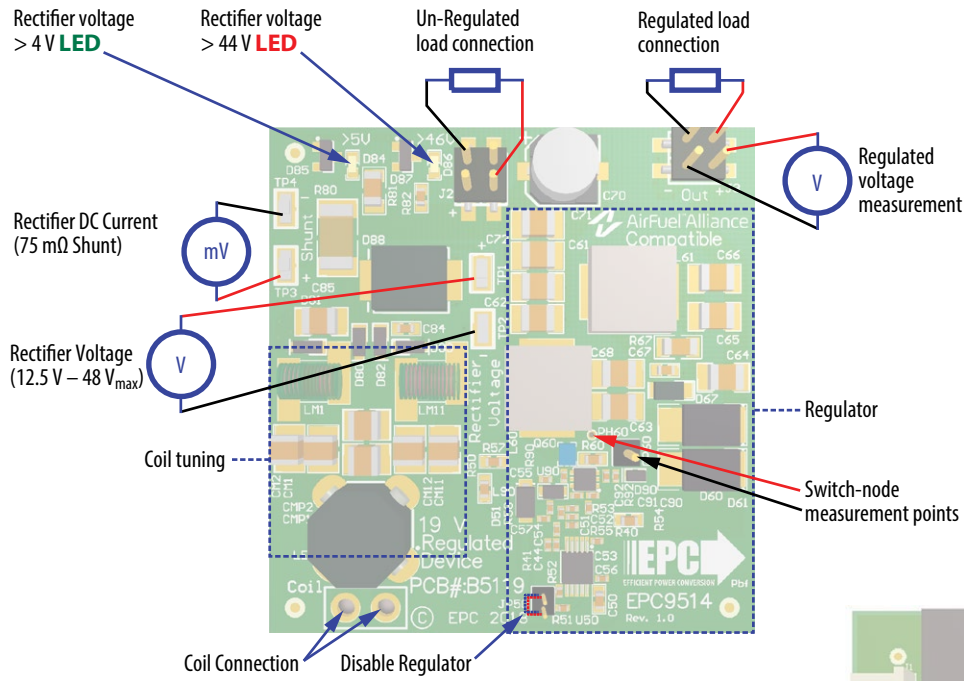


Figure 10: AirFuel Category 5 device board.

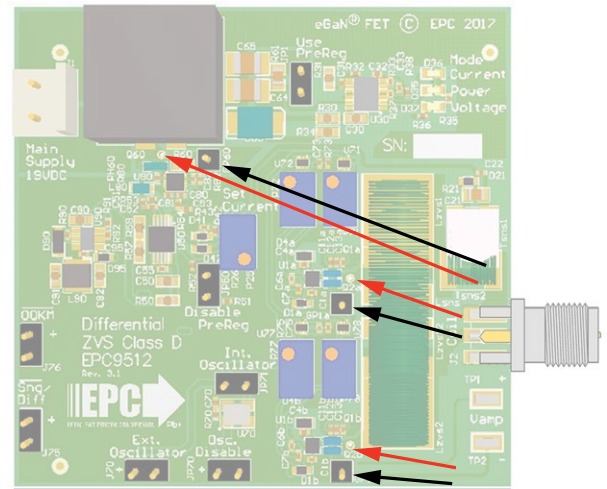


Figure 11: Measurement locations of switch node waveforms on EPC9512 amplifier board.

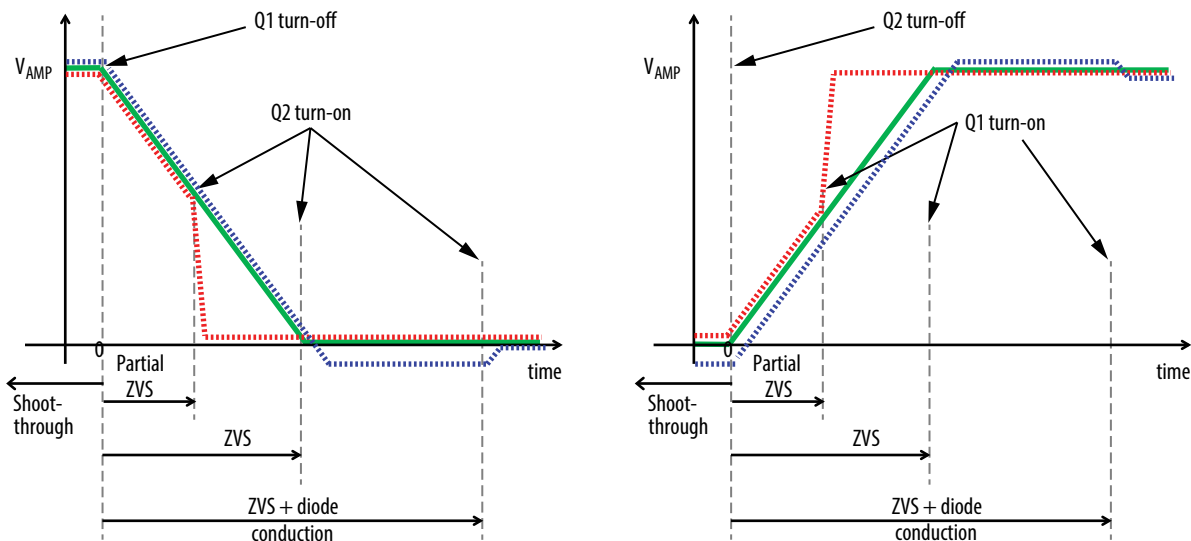


Figure 12: ZVS timing diagrams.

Table 4: Bill of Materials - Amplifier Board

Item	Qty	Reference	Part Description	Manufacturer	Part #
1	3	C1a, C1b, C80	1 μ F, 10 V	TDK	C1005X7S1A105M050BC
2	14	C2a, C2b, C4a, C4b, C5a, C5b, C70, C71, C72, C77, C78, C81, C130, C220	100 nF, 16 V	Würth	885012205037
3	3	C3a, C3b, C95	22 nF, 25 V	Würth	885012205052
4	10	C6a, C6b, C7a, C7b, C31, C32, C44, C75, C76, C82	22 pF, 50 V	Würth	885012005057
5	6	C11a, C11b, C12a, C12b, C13a, C13b	10 nF, 100 V	TDK	C1005X7S2A103K050BB
6	8	C14a, C14b, C15a, C15b, C16a, C16b, C17a, C17b	1 μ F, 100 V	TDK	C2012X7S2A105K125AB
7	1	C21 (not populated)	680 pF, 50 V	Murata	GRM155R71H681KA01D
8	1	C73 (not populated)	22pF, 50 V	Würth	885012005057
9	2	C133, C223 (not populated)	1 nF, 50 V	Murata	GRM1555C1H102JA01D
10	1	C22	390 pF, 50 V	Murata	GRM1555C1H391GA01D
11	2	C30, C50	100 nF, 100 V	Murata	GRM188R72A104KA35D
12	2	C33, C53	10 nF, 50 V	Murata	GRM155R71H103KA88D
13	1	C51	0.82 μ F, 10 V	Murata	GRM155R61A824KE15D
14	1	C52	100 pF	Murata	GRM1555C1H101JA01D
15	1	C54	22 nF, 50 V	Murata	GRM155R71H223KA12D
16	1	C55	1 μ F, 25 V	TDK	C1005X5R1E105M050BC
17	3	C61, C62, C63	22 μ F, 35 V	TDK	C3216JB1V226M160AC
18	2	C64, C65	4.7 μ F, 100 V	TDK	CGA6M3X7S2A475M200AB
19	1	C67 (not populated)	10 nF, 100 V	TDK	C1608X7R2A103K080AA
20	3	C90, C91, C92	1 μ F, 25 V	Würth	885012206076
21	2	C131, C221	1 nF, 50 V	Murata	GRM1555C1H102JA01D
22	2	Czvs1, Czvs2	1 μ F, 50 V	Würth	885012207103
23	1	D1	25 V, 11 A	Littelfuse	SMAJ22A
24	3	D1a, D1b, D95	40 V, 300 mA	ST	BAT54KFLM
25	13	D2a, D2b, D3a, D3b, D21, D40, D41, D42, D71, D72, D76, D77, D78	40 V, 30 mA	Diodes Inc.	SDM03U40
26	2	D4a, D4b	5 V1, 150 mW	Comchip Technology	CD0603-Z3V9
27	1	D35	LED 0603 yellow	Lite-On	LTST-C193KSKT-5A
28	1	D36	LED 0603 green	Lite-On	LTST-C193KGKT-5A
29	1	D37	LED 0603 red	Lite-On	LTST-C193KRKT-5A
30	1	D47	40 V, 30 mA	Diodes Inc.	SDM03U40-7
31	1	D60	200 V, 3 A	On Semiconductor	NRVBS3200T3G
32	1	D67 (not populated)	200 V, 1 A	Diodes Inc.	DFLS1200
33	1	D90	40 V, 1 A	Diodes Inc.	PD3S140-7
34	1	D221	3 V9, 150 mW	Bournes	CD0603-Z3V9
35	3	GP1a, GP1b, GP60	.1" male vert.	Würth	61300111121
36	1	J1	.156" male vert.	Würth	645002114822
37	1	J2	SMA board edge	Linx	CONSMA003.062
38	7	J70, J75, J76, JP1, JP50, JP70, JP71	.1" male vert.	Würth	61300211121
39	1	JMP1	DNP		
40	2	JP10, JP72	Jumper 100	Würth	60900213421
41	1	L60	100 μ H, 3 A	CoilCraft	MSD1514-104KE
42	1	L80	10H, 150 mA	Taiyo Yuden	LBR2012T100K
43	1	L90	47 μ H, 250 mA	Würth	7440329470
44	1	Lsns (not populated)	82 nH	CoilCraft	1515SQ-82NJEB
45	2	Lzvs1, Lzvs2	500 nH	CoilCraft	2929SQ-501JE
46	1	Lzvs12 (not populated)	DNP	CoilCraft	
47	1	P25 (not populated)	10 k Ω	Murata	PV37Y103C01B00
48	4	P71, P72, P77, P78 (not populated)	1 k Ω	Murata	PV37Y102C01B00
49	4	Q1a, Q1b, Q2a, Q2b	100 V, 160 m Ω	EPC	EPC8010
50	2	Q3a, Q3b	100 V, 3300 m Ω	EPC	EPC2038

(continued on next page)

Table 4: Bill of Materials - Amplifier Board (continued)

Item	Qty	Reference	Part Description	Manufacturer	Part #
51	1	Q60	200 V, 9 A, 43 mΩ	EPC	EPC2019
52	3	R2a, R2b, R82	20 Ω	Stackpole	RMCF0402JT20R0
53	2	R3a, R3b	27 k	Panasonic	ERJ-2GEJ273X
54	2	R4a, R4b	4.7 Ω	Panasonic	ERJ-2GEJ4R7X
55	1	R21	33 Ω, 1/2 W	Panasonic	ERJ-P06J330V
56	1	R25	4.3 k 1%	Panasonic	ERJ-2RKF4301X
57	1	R26	6.81 k 1%	Panasonic	ERJ-2RKF6811X
58	1	R30 (not populated)	100 Ω	Panasonic	ERJ-3EKF1000V
59	1	R31	82.5 k 1%	Panasonic	ERJ-3EKF8252V
60	1	R32	8.2 k 1%	Panasonic	ERJ-2RKF8201X
61	1	R33	56 k	Panasonic	ERJ-2RKF5602X
62	1	R34	100 Ω	Panasonic	ERJ-3EKF1000V
63	2	R35, R36	634 Ω	Panasonic	ERJ-2RKF6340X
64	1	R37	150 k 1%	Panasonic	ERJ-2RKF1503X
65	2	R38, R91	49.9 k 1%	Panasonic	ERJ-2RKF4992X
66	2	R40, R130	316 k	Panasonic	ERJ-3EKF3163V
67	4	R41, R49, R131, R221	6.04 k	Panasonic	ERJ-2RKF6041X
68	1	R42	41.2 k	Panasonic	ERJ-2RKF4122X
69	1	R43	20.5 k	Panasonic	ERJ-2RKF2052X
70	2	R44, R90	100 k 1%	Panasonic	ERJ-2RKF1003X
71	1	R48	15.4 k	Panasonic	ERJ-2RKF1542X
72	1	R50	10 Ω	Panasonic	ERJ-3EKF10R0V
73	1	R51	124 k 1%	Panasonic	ERJ-2RKF1243X
74	1	R52	82.5 k 1%	Panasonic	ERJ-2RKF8252X
75	1	R53	12 Ω	Panasonic	ERJ-2RKF12R0X
76	1	R54	0 Ω	Yageo	RC0402JR-070RL
77	1	R55	23.2 k	Panasonic	ERJ-2RKF2322X
78	1	R57	160 k	Panasonic	ERJ-3EKF1603V
79	1	R58	33 k	Panasonic	ERJ-3GEYJ333V
80	1	R60	20 mΩ, 0.4 W	Vishay Dale	WSLP0603R0200FEB
81	1	R61	75 mΩ, 0.25 W	Vishay Dale	RCWE080575L0FKEA
82	1	R67 (not populated)	10 k 5%, 2/3 W	Panasonic	ERJ-P08J103V
83	1	R70	47 k	Panasonic	ERJ-2RKF4702X
84	2	R71, R78	180 Ω	Panasonic	ERJ-2RKF1800X
85	2	R72, R77	51 Ω	Panasonic	ERJ-2RKF51R0X
86	3	R73, R75, R76	10 k	Panasonic	ERJ-2GEJ103X
87	1	R80	2.2 Ω	Yageo	RC0402JR-072R2L
88	1	R92	9.53 k, 1%	Panasonic	ERJ-2RKF9531X
89	2	R132, R222	18 k 1%	Panasonic	ERJ-2RKF1802X
90	2	R133, R223	6.8 k 1%	Panasonic	ERJ-2RKF6801X
91	1	R134	470 k	Panasonic	ERJ-2RKF4703X
92	1	R220	71.5 k	Panasonic	ERJ-3EKF7152V
93	1	R224	330 k	Panasonic	ERJ-2RKF3303X
94	2	TP1, TP2	SMD probe loop	Keystone	5015
95	1	Tsns1 (not populated)	10 μH, 1:1, 96.9%	CoilCraft	PF3215-103ME
96	1	Tsns2	1:20 current Xmr	CoilCraft	CST7030-020LB
97	2	U1a, U1b	100 V eGaN driver	Texas Instruments	LM5113TM
98	1	U30	Power & current monitor	Linear	LT2940IMS#PBF
99	1	U50	Boost controller	Texas Instruments	LM3481MM/NOPB
100	1	U70	Pgm Osc.	EPSON	SG-8002CE-PHB-6.780 MHz
101	2	U71, U77	2 In NAND	Fairchild	NC7SZ00L6X
102	2	U72, U78	2 In AND	Fairchild	NC7SZ08L6X
103	1	U80	Gate driver with LDO	Texas Instruments	UCC27611DRV
104	1	U90	1.4 MHz, 24 V, 0.5 A buck	MPS	MP2357DJ-LF
105	2	U130, U220	Comparator	Texas Instruments	TLV3201AIDBVR

Table 5: Bill of Materials - Source Coil

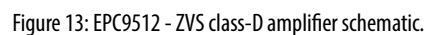
Item	Qty	Reference	Part Description	Manufacturer	Part #
1	1	C2	7.5 pF	Johanson	102S42E7R5CV3E
2	2	C3, Ctrmb	220 pF	Johanson	201S42E221JV4E
3	1	J1	SMA PCB edge	Linx	CONSMA013.062
4	1	Coil1	Class 4 small	NuCurrent	NC20-T091M01E-228-150-1R40

Table 6: Bill of Materials - Category 3 Device Board

Item	Qty	Reference	Part Description	Manufacturer	Part #
1	1	C44	Capacitor, 100 pF, 25 V	Würth	885012205038
2	1	C50	Capacitor, 100 nF, 100 V	Murata	GRM188R72A104KA35D
3	1	C51	Capacitor, 4.7 μ F, 6.3 V	Murata	GRM155R60J475ME47D
4	1	C52	Capacitor, 100 pF, 50 V	Würth	885012005061
5	1	C53	Capacitor, 220 pF, 50 V	Würth	885012206079
6	2	C55, C90	Capacitor, 1 μ F, 25 V	TDK	C1005X5R1E105M050BC
7	3	C56, C57, C91	Capacitor, 100 nF, 16 V	Würth	885012205037
8	7	C61, C62, C63, C68, C71, C72, C85	Capacitor, 10 μ F, 50 V	Taiyo Yuden	UMK325BJ106MM-T
9	3	C64, C65, C66	Capacitor, 22 μ F, 35 V	TDK	C3216JB1V226M160AC
10	1	C84	Capacitor, 100 nF, 50 V	Würth	885012206095
11	1	C92	Capacitor, 22 pF, 50 V	Würth	885012005057
12	1	CM1	Capacitor, 560 pF size 1111	Vishay	VJ1111D561KXDAT
13	1	CM2	Capacitor, 20 pF size 1111	Vishay	VJ1111D200JXRAJ
14	1	CM12	Capacitor, 680 pF size 1111	Vishay	VJ1111D681KXDAT
15	1	D51	Schottky Diode, 30 V, 500 mA	ST	STPS0530Z
16	1	D60	Schottky Diode, 100 V, 3 A	ST	STPS3H100UF
17	4	D80, D81, D82, D83	Schottky Diode, 40 V, 1 A	Diodes Inc.	PD3S140-7
18	1	D84	LED 0603 Green	Würth	150060VS75000
19	1	D85	Zener Diode, 2.7 V, 250 mW	NXP	BZX84-C2V7,215
20	1	D86	LED 0603 Red	Würth	150060SS75000
21	1	D87	Zener Diode, 33 V, 250 mW	NXP	BZX84-C33,215
22	1	D88	TVS Diode, 35 V, 8.2 A	Littelfuse	SMAJ30A
23	1	J1	Category 3 Coil	NuCurrent	NC20-R070L03E-079-063-0R71
24	1	J3	.1" Male Vert. SMD 2 x 2	Amphenol FCI	95278-101A04LF
25	2	L60, L61	Inductor, 22 μ H, 4.3 A	Vishay Dale	IHLP3232DZER220M11
26	1	L90	Inductor, 10 μ H, 150 mA	Taiyo Yuden	LBR2012T100K
27	1	LE1	Inductor, 18 μ H, 3.8 mA	Eaton	CMS1-4-R
28	2	LM1, LM11	Inductor, 82 nH	Würth	744912182
29	1	Q60	eGaN FET, 200 V, 9 A, 43 m Ω	EPC	EPC2019
30	1	R40	Resistor, 17.8 k Ω 1%, 1/10W	Panasonic	ERJ-3EKF1782V
31	1	R41	Resistor, 6.04 k Ω 1%, 1/10W	Panasonic	ERJ-2RKF6041X
32	1	R50	Resistor, 10 Ω 1%, 1/10W	Panasonic	ERJ-3EKF10R0V
33	1	R51	Resistor, 124 k Ω 1%, 1/10W	Panasonic	ERJ-2RKF1243X
34	1	R52	Resistor, 62 k Ω 1%, 1/10W	Panasonic	ERJ-2RKF6202X
35	1	R53	Resistor, 12 Ω 1%, 1/10W	Panasonic	ERJ-2RKF12R0X
36	1	R54	Resistor, 0 Ω JUMPER, 1/16W	Yageo	RC0402JR-070RL
37	1	R57	Resistor, 1 m Ω 1%, 1/10W	Panasonic	ERJ-3EKF1004V
38	1	R58	Resistor, 150 k Ω 1%, 1/10W	Panasonic	ERJ-2RKF1503X
39	1	R60	Resistor, 40 m Ω 1%, 0.4W	Vishay Dale	WSLP0603R0400FEB
40	1	R80	Resistor, 75 m Ω 1%, 2W	Stackpole	CSRN2512FK75L0
41	1	R81	Resistor, 4.7 k Ω 1%, 1/4W	Stackpole	RMCF1206FT4K70
42	1	R82	Resistor, 422 Ω 1%, 1/10W	Yageo	RMCF0603FT422R
43	1	R90	Resistor, 2.2 Ω 5%, 1/16W	Yageo	RC0402JR-072R2L
44	1	R92	Resistor, 20 Ω 5%, 1/16W	Stackpole	RMCF0402JT20R0
45	4	TP1, TP2, TP3, TP4	SMD Probe Loop	Keystone	5015
46	1	U50	IC, Boost Controller	Texas Instruments	LM3481MM/NOPB
47	1	U90	IC, Gate Driver with LDO	Texas Instruments	UCC27611DRV

Table 7: Bill of Materials - Category 5 Device Board

Item	Qty	Reference	Part Description	Manufacturer	Part #
1	1	C44	100 pF, 25 V	Würth	885012205038
2	1	C50	100 nF, 100 V	Murata	GRM188R72A104KA35D
3	4	C51, C56, C57, C91	100 nF, 16 V	Würth	885012205037
4	1	C53	220 pF, 50 V	Murata	GRM155R71H221KA01D
5	2	C55, C90	1 μ F, 25 V	TDK	C1005X5R1E105M050BC
6	6	C61, C62, C63, C68, C71, C72	10 μ F, 50 V	Taiyo Yuden	UMK325BJ106MM-T
7	3	C64, C65, C66	22 μ F, 35 V	TDK	C3216JB1V226M160AC
8	1	C67	10nF, 200 V	Kemet	C0603C103K2RACTU
9	1	C70	10 μ F, 50 V	Nichicon	UZR1H100MCL1GB
10	1	C84	100 nF, 50 V	Murata	GRM188R71H104KA93D
11	1	C85	10 μ F, 50 V	Taiyo Yuden	UMK325BJ106MM-T
12	1	C92	22 pF, 50 V	Würth	885012005057
13	2	CM1, CM11	390 pF	Vishay	VJ1111D391KXLAJ
14	1	Coil	Receive Coil	NuCurrent	NC20-T025L01E-152-115-0R75
15	1	D51	30 V, 500 mA	ST	STPS0530Z
16	1	D60	100 V, 5 A	Diodes	PDS5100-13
17	1	D67	200 V, 1 A	Diodes Inc.	DFLS1200
18	4	D80, D81, D82, D83	60 V 1 A	Diodes Inc.	PD3S160-7
19	1	D84	LED 0603 Green	Lite-On	LTST-C193KGKT-5A
20	1	D85	2.7 V, 250 mW	Nexperia	BZX84-C2V7,215
21	1	D86	LED 0603 Red	Lite-On	LTST-C193KRKT-5A
22	1	D87	43 V, 250 mW	Nexperia	BZX84-C43,215
23	1	D88	44 V, 51.6 A	Littelfuse	SMDJ36A
24	1	GP60	.1" Male Vert.	Würth	61300111121
25	2	J2, J3	.1" Male Vert.	Amphenol FCI	95278-101A04LF
26	1	JP50	.05" 2 pos Male Vert	Sullins	GRPB021VWVN-RC
27	2	L60, L61	22 μ H, 4.3A	Vishay Dale	IHLP3232DZER220M11
28	1	L90	10 μ H, 150 mA	Taiyo Yuden	LBR2012T100K
29	1	LE1	25 μ H, 5.3 A	Eaton	CMS2-1-R
30	2	LM1, LM11	82 nH	Würth	744912182
31	1	Q60	100 V, 11 A, 16 m Ω	EPC	EPC2016C
32	1	R40	84.5 k Ω 1%	Panasonic	ERJ-3EKF8452V
33	1	R41	6.04 k Ω	Panasonic	ERJ-2RKF6041X
34	1	R50	10 Ω	Panasonic	ERJ-3EKF10R0V
35	1	R51	124 k Ω 1%	Panasonic	ERJ-2RKF1243X
36	1	R52	56.2 k Ω 1%	Yageo	RC0402FR-0756K2L
37	1	R53	2.32 k Ω	Yageo	RC0402FR-072K32L
38	1	R54	300 Ω	Yageo	RC0402JR-07300RL
39	1	R57	2.49 M Ω 1%	Yageo	RC0603FR-072M49L
40	1	R58	150 k Ω 1%	Panasonic	ERJ-2RKF1503X
41	1	R60	22 m Ω , 0.4 W	Vishay Dale	WSLP0603R0220FEB
42	1	R67	10 k Ω , 5% 2/3 W	Panasonic	ERJ-P08J103V
43	1	R80	75 m Ω , 1 W	Stackpole	CSRN2512FK75L0
44	1	R81	4.7 k Ω	Stackpole	RMCF1206FT4K70
45	1	R82	422 Ω	Yageo	RMCF0603FT422R
46	1	R90	2.2 Ω	Yageo	RC0402JR-072R2L
47	1	R92	20 Ω	Stackpole	RMCF0402JT20R0
48	4	TP1, TP2, TP3, TP4	SMD probe loop	Keystone	5015
49	1	U50	Boost Controller	Texas Instruments	LM3481MM/NOPB
50	1	U90	Gate Driver with LDO	Texas Instruments	UCC27611DRV



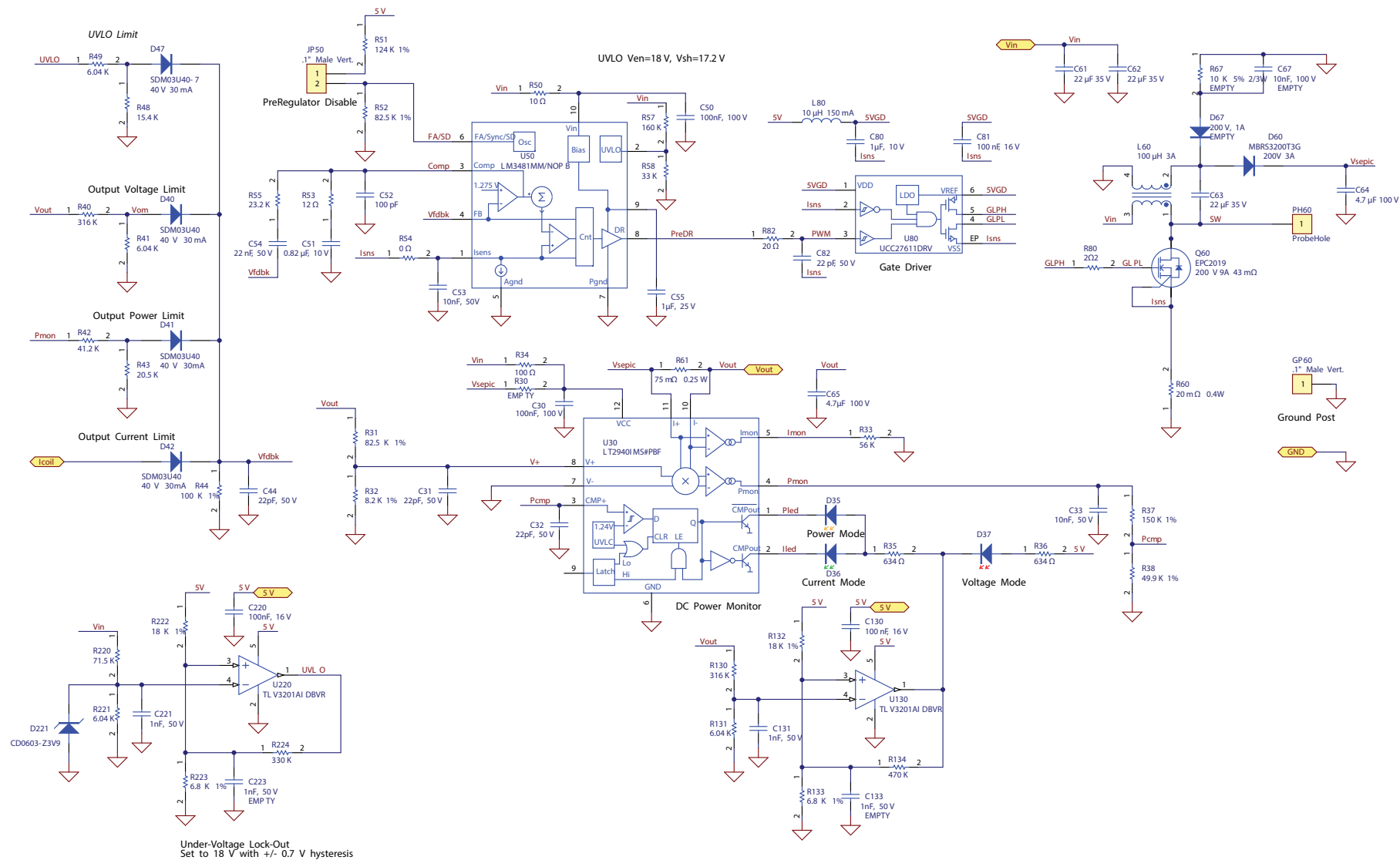
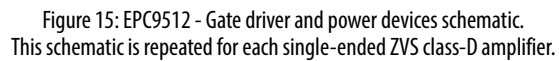


Figure 14: EPC9512 - Pre-regulator schematic for wireless power transfer source.



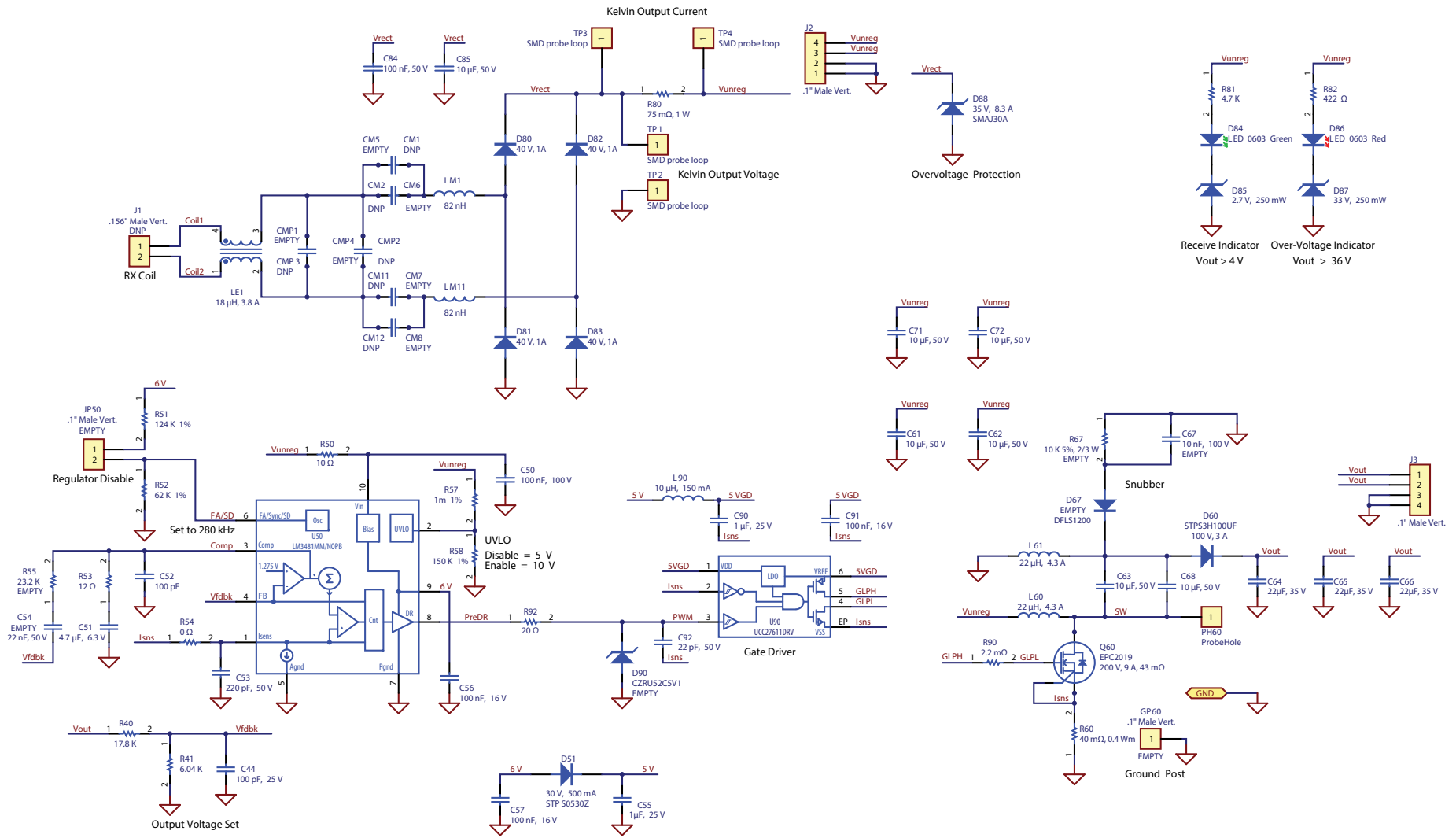
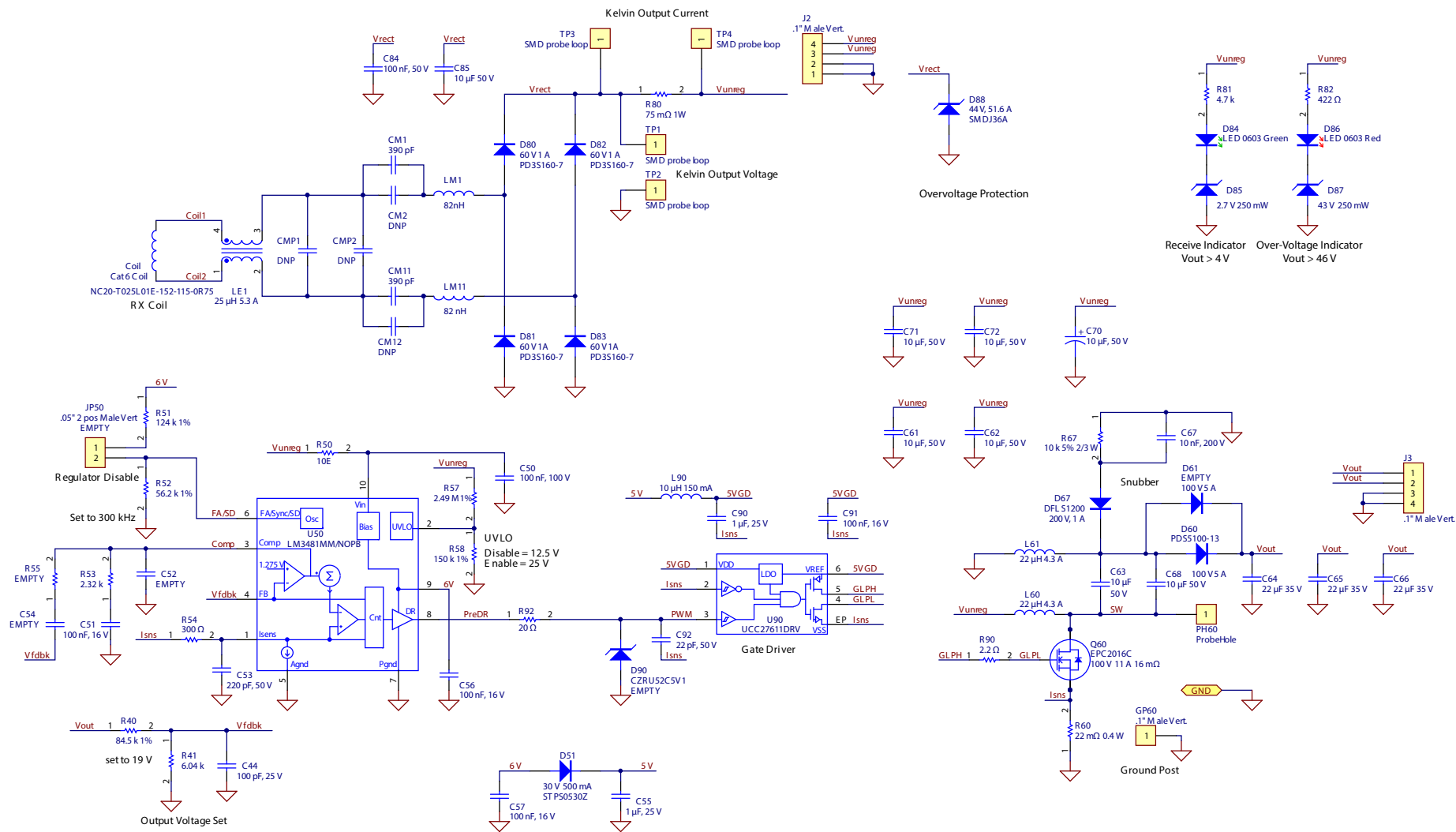


Figure 16: EPC9513 schematic



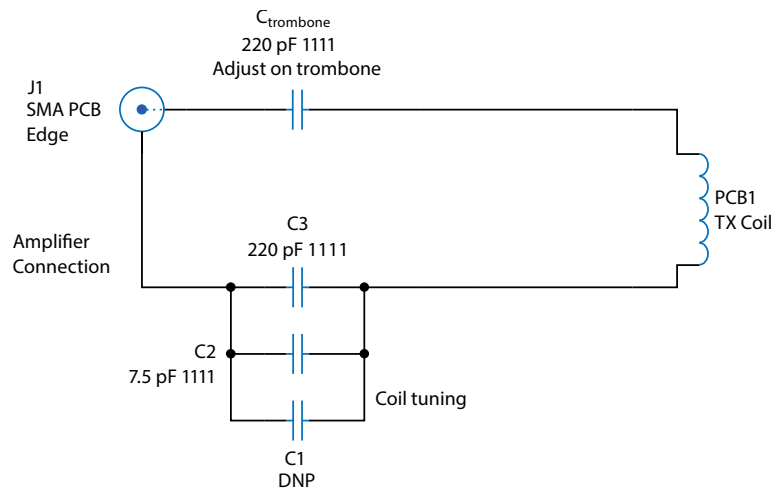


Figure 18: Class 4 source board schematic.



EPC would like to acknowledge Würth Elektronik (www.we-online.com) for their support of this project.

Würth Elektronik is a premier manufacturer of electronic and electromechanical passive components. EPC has partnered up with WE for a variety of passive component requirements due to the performance, quality and range of products available. EPC9129 system features various Würth Elektronik product lines including capacitors, LEDs and connectors.

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EPC would like to acknowledge Johanson Technology (www.johansontechnology.com) for their support of this project. Information on the capacitors used in this kit can be found at <http://www.johansontechnology.com/S42E>.



EPC would like to acknowledge NuCurrent (www.NuCurrent.com) for their support of this project.

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Note that this demonstration kit is not compliant with any wireless power standard. It can be used to evaluate wireless power transfer according to the standards and is meant as a tool to evaluate eGaN® FETs and eGaN® ICs in this application.