Application Note 90

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Current Sources for Fiber Optic Lasers

A Compendium of Pleasant Current Events

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INTRODUCTION

A large group of fiber optic lasers are powered by DC current. Laser drive is supplied by a current source with modulation added further along the signal path. The current source, although conceptually simple, constitutes an extraordinarily tricky design problem. There are a number of practical requirements for a fiber optic current source and failure to consider them can cause laser and/or optical component destruction.

Design Criteria for Fiber Optic Laser Current Sources

Figure 1 shows a conceptual laser current source. Inputs include a current output programming port, an output current clamp and an enable command. Laser current is the sole output. This block diagram is deceptively simple. In practice, a laser current source must meet a number of practical requirements, some quite subtle. The key to a successful design is a thorough understanding of individual system requirements. Various approaches suit different sets of freedoms and constraints, although all must address some basic concerns.

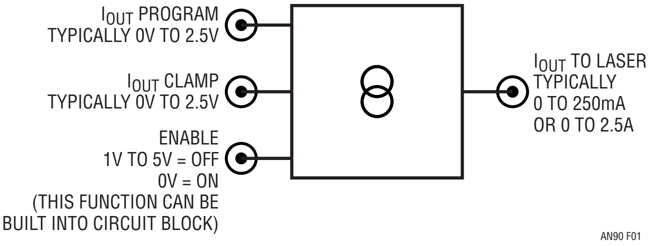

Figure 1. Conceptual Laser Current Source is Deceptively Simple. Practical System Issues and Laser Vulnerability Necessitate Careful Design

There are two basic sets of concerns for laser current sources: performance and protection. Performance issues include the current source's magnitude and stability under all conditions, output connection restrictions, voltage compliance, efficiency, programming interface and power requirements.

Protection features must be included to prevent laser and optical component damage. The laser, an expensive and delicate device, must be protected under all conditions, including supply ramp up and down, improper control input commands, open or intermittent load connections and "hot plugging."

Detailed Discussion of Performance Issues

It is useful to expand on the above cursory discussion to clarify design goals. As such, each previously called out issue is treated in greater detail below.

Required Power Supply

The available power supply should be defined. A single rail 5V supply is presently the most common and desirable. Supply tolerances, typically ±5%, must be accounted for. System distribution voltage drops may result in surprisingly low rail voltages at the point of load. Occasionally, split rails are available, although this is relatively rare. Additionally, split rail operation can complicate laser protection, particularly during supply sequencing. See "Laser Protection Features" below for additional comment.

Output Current Capability

Low power lasers operate on less than 250mA. Higher power types can require up to 2.5A.

Output Voltage Compliance

Current source output voltage compliance must be able to accomodate the laser's forward junction drop and any additional drops in the drive path. Typically, voltage compliance of 2.5V is adequate.

Efficiency

Heat build up in fiber optic systems is often a concern due to space limitations. Accordingly, current source efficiency can be an issue. At low current, linear regulation is often adequate. Switching regulator based approaches may be necessary at higher current.

Laser Connection

In some cases, the laser may float off ground; other applications require grounded anode or cathode operation. Grounding the anode seemingly mandates a negative supply but single rail operation can be retained if switching regulator techniques are employed.

Output Current Programming

Output current is set by a programming port voltage. The voltage may be derived from a potentiometer, DAC or filtered PWM. Typically, a range of 0V to 2.5V corresponds to 0A to 250mA or 0A to 2.5A. Set point accuracy is usually within 0.5%, although better tolerances are readily achievable. Output current stability, discussed below, is considerably tighter.

Stability

The current source should be well regulated against line, load and temperature changes. Line and load induced variations should be held well within 0.05%, with typical temperature drifts of 0.01%. Judicious component choice can considerably improve these figures.

Noise

Current source noise, which can modulate laser output, must be minimized. Typically, noise bandwidth to 100MHz is of interest. A linearly regulated current source has inherently low noise and usually presents no problems. Switching regulator based current sources require special techniques to maintain low noise.

Transient Response

The current source does not need fast transient response but it cannot overshoot the programmed current under any circumstances. Such overshoots can damage the laser or associated optical components.

Detailed Discussion of Laser Protection Issues

Overshoot

As noted above, outputs overshooting the nominal programmed current can be destructive. Any possible combination of improper control input or power supply turn on/off characteristics must be accounted for. Also, any spurious laser current under any condition is impermissible. Note that portions of the current source circuitry may have undesired and unpredictable responses during supply ramp up/down, complicating design.

Enable

An enable line allows shutting the current source output off. The enable line can also be used to hold current output off during supply ramp up, preventing undesired outputs. This can be tricky because the enable signal circuitry may be powered by the same supply that runs the laser. The enable signal must reliably operate independent of power supply turn-on profile. Optionally, the enable function can be self-contained within the current source, eliminating the necessity to generate this signal.

Output Current Clamp

The output current clamp sets maximum output current, overriding the output current programming command. This voltage controlled input can be set by a potentiometer, DAC or filtered PWM.

Open Laser Protection

An unprotected current source's output rises to maximum voltage if the load is disconnected. This circumstance can lead to "hot plugging" the laser, a potentially destructive event. Intermittent laser connections can produce similar undesirable results. The current source output should latch off if the load disconnects. Recycling power clears the latch but only if the load has been established.

The preceding discussion dictates considerable care when designing laser current sources. The delicate, expensive load, combined with the uncertainties noted, should promote an aura of thoughtful caution.[1] The following circuit examples (hopefully) maintain this outlook while simultaneously presenting practical, usable circuits. A variety of approaches are shown, in keeping with the broad area of

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Note 1. "For Fools Rush in Where Angels Fear to Tread." An essay on criticism, A. Pope. 1711.

application. The designs can be directly utilized or serve as starting points for specific cases.

Basic Current Source

Figure 2, a basic laser current source, supplies up to 250mA via Q1. This circuit requires both laser terminals to float. The amplifier controls laser current by maintaining the 1Ω shunt voltage at a potential dictated by the programming input. Local compensation at the amplifier stabilizes the loop and the 0.1µF capacitor filters input commands, assuring the loop never slew limits. This precaution prevents overshoot due to programming input dynamics. The enable input turns off the current source by simultaneously grounding Q1's base and starving the amplifier's "+" input while biasing the "–" input high. This combination also insures the amplifier smoothly ramps to the desired output current when enable switches low. The enable input must be addressed by an external "watchdog" which switches after the power supply has been verified to be within operating limits. Because the external circuitry may operate from the same supply as the current source, the enable threshold is set at 1V. The 1V threshold assures the enable input will dominate the current source output at low supply voltages during power turn on. This prevents spurious outputs due to unpredictable amplifier behavior below minimum supply voltage.

High Efficiency Basic Current Source

The preceding circuit uses Q1's linear regulation to close the feedback loop. This approach offers simplicity at the expense of efficiency. Q1's power dissipation can approach 1W under some conditions. Many applications permit this but some situations require heating minimization. Figure 3 minimizes heating by replacing Q1 with a step-down switching regulator. The switched mode power delivery eliminates almost all of the transistor's heat.

The figure shows similarities to Figure 2's linear approach, except for the LTC1504 switching regulator's addition. It is useful to liken the switching regulator's input (V_{CC}), feedback (FB) and output (V_{SW}) to the transistor's collector, base and emitter. This analogy reveals the two circuits to have very similar operating characteristics, with the switched mode version enhancing efficiency. The LTC1504's output LC filter introduces phase shift, necessitating attention to loop compensation. The amplifier's local rolloff is similar to Figure 2, although phase leading AC feedback elements (0.01µF and 0.033µF capacitors) are required for good loop damping. In all other respects, including enable and programming input considerations, this circuit's operation is identical to Figure 2.

Grounded Cathode Current Source

Figure 4 allows the laser's cathode to be grounded, as is sometimes required, by sensing anode current. It utilizes A1, a device with 500mA output capability and programmable output current limit. A1 senses output current across the 1Ω shunt, with limiting controlled by the circuit's current programming input. A1 is set up as a unity-gain follower with respect to the laser, allowing its positive input to serve as a laser voltage clamp input. At laser voltages below the V_{CLAMP} input, A1 appears as a current source, controlled by the current programming

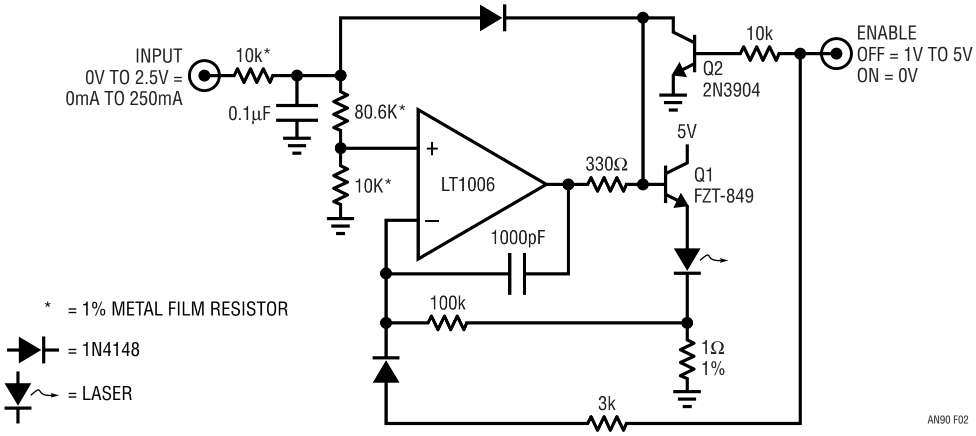

Figure 2. Basic Current Source Requires Off-Ground Operation of Laser Terminals. Amplifier Controls Current by Comparing 0.1Ω Shunt to Input. Biasing Enable Until Supply is Verified Prevents Spurious Outputs

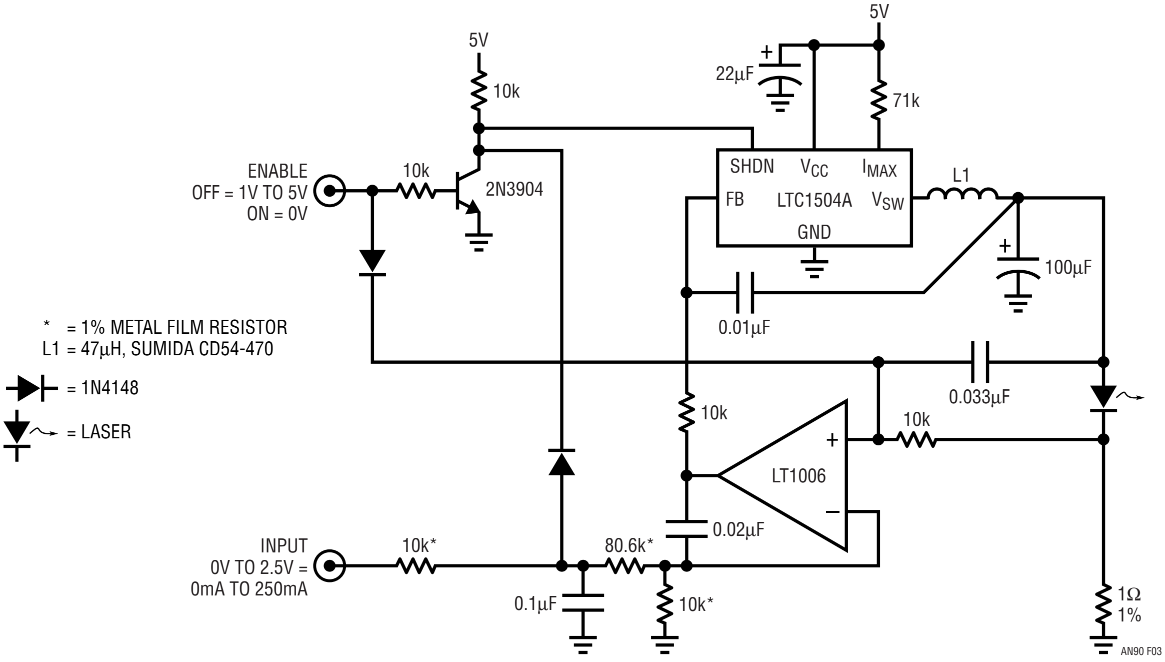

Figure 3. Switching Regulator Replaces Figure 2's Q1, Providing Higher Efficiency. Feedback Control and Enable Input Considerations are as Before

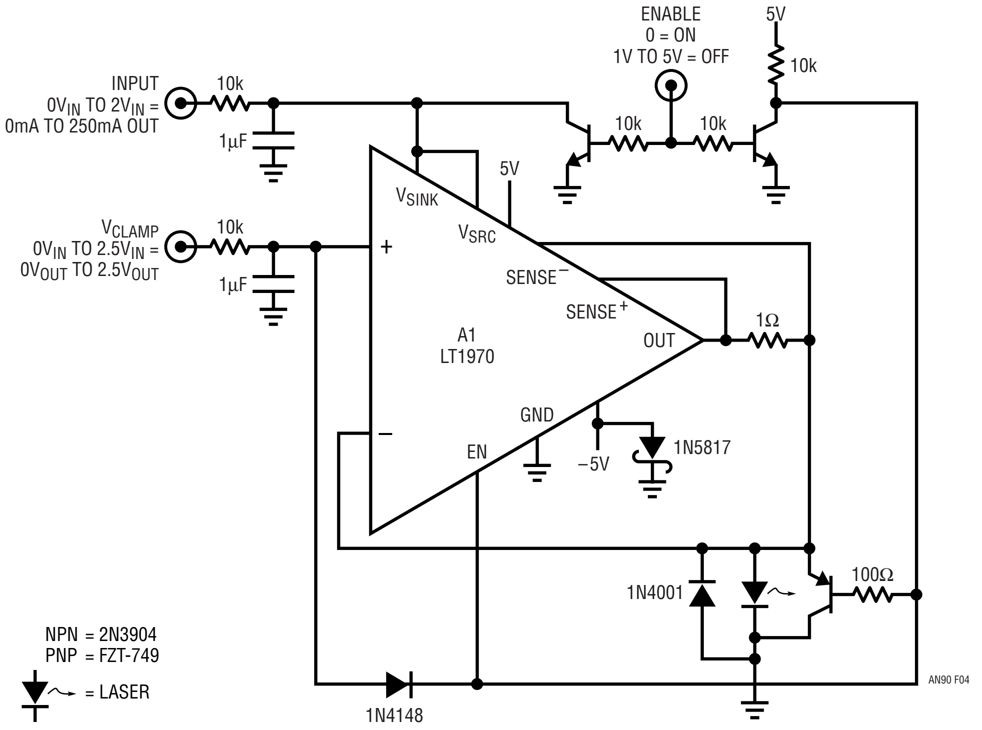

Figure 4. LT1970 Power Ampifier/Current Source Permits Grounding Laser Cathode, Although Requiring Split Rails. Appropriate Modifications would Allow Grounded Anode Operation. Enable Input Must be Biased Until Supplies are Verified

input's setting. At laser voltages equaling or above the V_{CLAMP} input, A1 is a voltage source, controlled by V_{CLAMP}'s value. This permits the V_{CLAMP} input to limit maximum voltage across the laser terminals.

The enable function operates similarly to previous descriptions and the 1μF capacitors restrict output movement to safe, well damped speeds. The diode shunting the laser prevents reverse bias during power supply sequencing. The 1N5817 protects against uncontrolled positive outputs if the negative supply drops out or sequences too slowly. This circuit's simplicity and laser connection versatility (appropriate modifications permit grounded anode operation) are attractive but A1's negative supply requirement may be detrimental. The negative supply complicates the external "watchdog" circuitry required for the enable input. In the worst case, it simply may not be available in the host system.

Single Supply, Grounded Cathode Current Source

Figure 5 preserves Figure 4's grounded cathode operation while operating from a single supply. This circuit is reminiscent of Figure 2, with a notable exception. Here, differential amplifier A2 senses across a shunt in the laser anode, permitting cathode grounding. A2's gain-scaled output feeds back to A1 for loop closure. Loop compensation and enable input considerations are related to previous examples and, as before, Q1 could be replaced with a switching regulator.

Fully Protected, Self-Enabled, Grounded Cathode Current Source

All of Figure 5's elements are repeated in Figure 6; no additional comment on them is necessary. However, three new features appear, allowing this circuit to operate in a fully protected and self-contained fashion. The circuit monitors its power supply and "self-enables" when the supply is within limits, eliminating the "enable" port and the external "watchdog" previously required. A settable current clamp and open laser protection prevent laser damage.

The self-enable is designed around an LT1431 shunt regulator. It has the highly desirable property of maintaining a predictable open collector output when operating below its minimum supply voltage. At initial turn on, supply voltage is very low (e.g., 1V), the LT1431's output does not switch and current flows to Q3's base. Q3 turns on, preventing Q1's base from receiving bias. Additionally, the circuit's current programming input is pulled down and A1's "–" input is driven. This arrangement ensures that the laser cannot receive current until Q3 turns off. Also, when Q3 does go off, A1's output will cleanly ramp up to the desired programmed current. The resistor values at the LT1431's "REF" input dictate the device will go low when V_{SUPPLY} passes through 4V. This potential ensures proper circuit operation. Supply start-up waveforms appear in Figure 7. Trace A, the nominal 5V rail, ramps for 3ms before arriving at 5V. During this interval, the LT1431

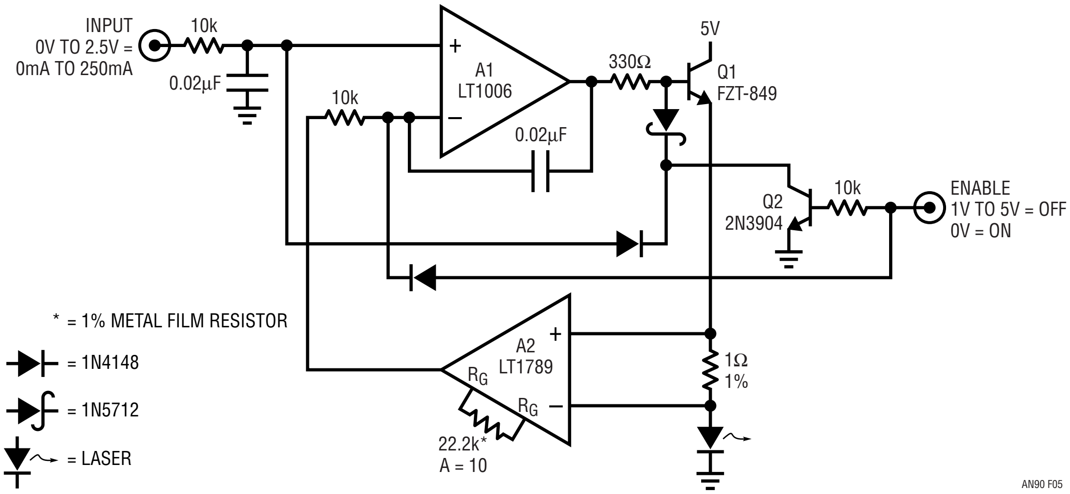

Figure 5. Differentially Sensed Shunt Voltage Allows Grounded Cathode Laser Drive with Single Supply. Loop and Enable Input Considerations Derive from Previous Figures

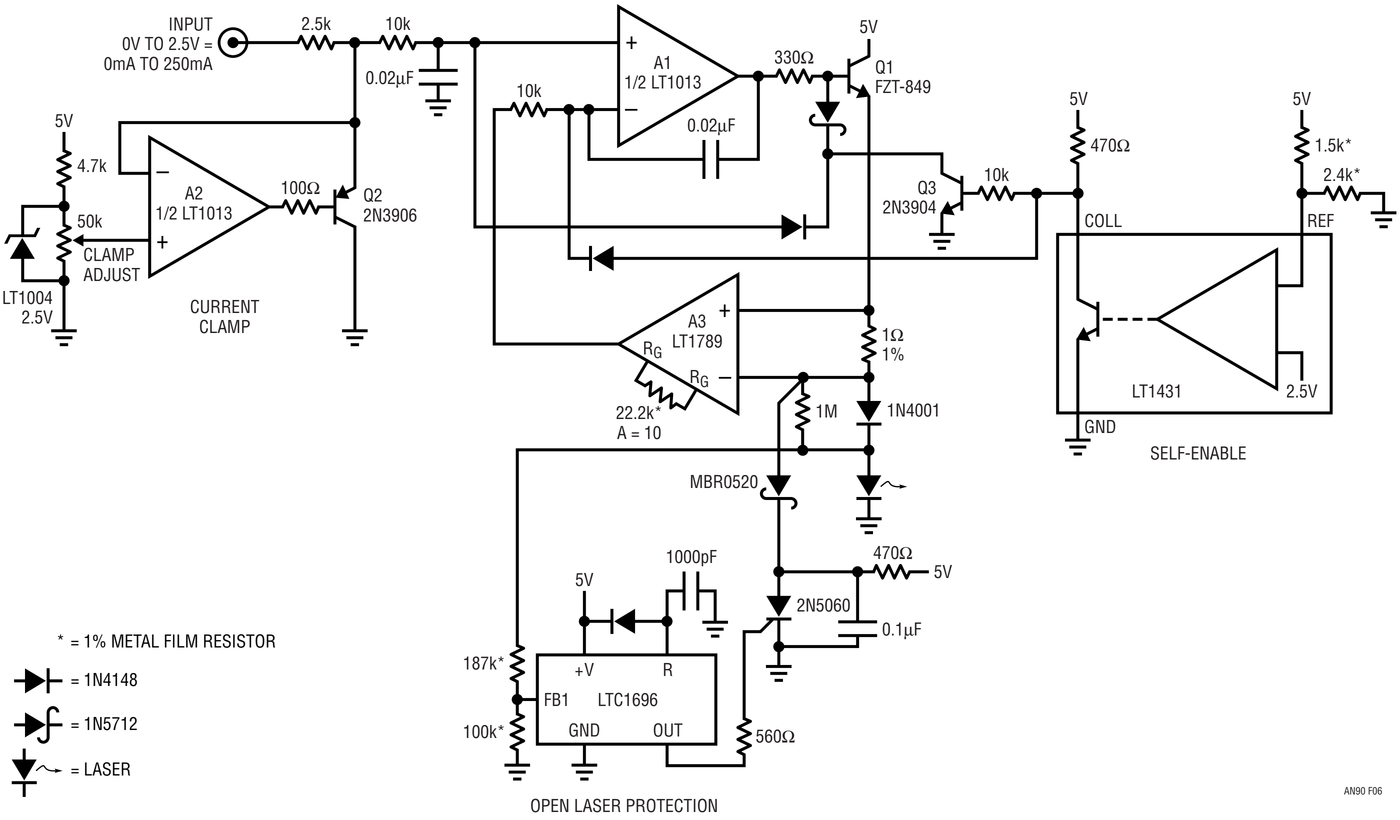

Figure 6. Figure 5's Circuit, Augmented with "Self-Enable," Monitors Power Supply, Operates when V_{SUPPLY} = 4V. Current and Open Laser Clamps Protect Laser

(trace B) follows the ramp, biasing Q3 on. A1's output (trace C) is uncontrolled during this period, Q1's emitter (trace D), however, is cut off due to Q3's conduction and cannot pass the disturbance. As a result, the laser conducts no current (trace E) during this time. When the supply (trace A) ramps beyond 4V (just before the photo's 4th vertical division), the LT1431 switches low (trace B), Q3 switches off and the circuit "self-enables." A1's output (trace C) ramps up, with Q1's emitter (trace D) and laser current (trace E) slaved to its movement. This action prevents any undesired current in the laser during supply turn on, regardless of unpredictable circuit behavior at low supply voltages.

Supply turn on is not the only time laser current must be controlled. Response to programming input changes must be similarly well behaved. Figure 8 shows laser current response (trace B) to a programming input step (trace A). Damping is clean, with no hint of overshoot.

The circuit also includes open laser protection. If the current source operates into an open load (no laser), it will produce maximum voltage at the laser output terminals. This circumstance can lead to "hot plugging" the laser, a potentially destructive event. Intermittent laser connections can produce similar undesirable results. The LTC1696 overvoltage protection controller guards against open laser operation. This device's output latches high when its feedback input (FB) exceeds 0.88V. Here, the FB pin is biased so that laser output voltage exceeding 2.5V forces the LTC1696 high, triggering the SCR to shunt current away from the laser. The 470Ω resistor supplies SCR holding current and the diodes insure no current flows in the output.

Figure 9 details events with a properly connected laser at supply turn on. Trace A is the supply, trace B the laser voltage, trace C the LTC1696 output and trace D the laser current. The waveforms show laser voltage (trace B) rising to about 2V at supply turn on (trace A). Under these normal conditions, the LTC1696 output (trace C) stays low and laser current (trace D) rises to the programmed value.

Figure 10 shows what happens when the circuit is turned on into an open laser connection. Trace assignments are identical to the previous photo. At supply turn on (trace A), the laser voltage (trace B) transitions beyond the 2.5V open laser threshold. The LTC1696 output (trace C) goes high, the SCR latches and no current flows in the shunted laser line (trace D). Once this occurs, power must be recycled to reset the LTC1696-SCR latch. If the laser has not been properly connected, the circuit will repeat its protective action. Open laser protection is not restricted to turn on. It will also act if laser connection is lost at any time during normal circuit operation.

A final protection feature in Figure 6 is a current clamp. It prevents uncontrolled programming inputs from being transmitted by clamping them to a settable level. A2, Q2 and associated components form the clamp. Normally, A2's "+" input is above the circuit's programming input (Q2's emitter voltage), A2's output is high and Q2 is off. If the programming input exceeds A2's "+" input level, A2 swings low, Q2 comes on and the amplifier feedback controls Q2's emitter to the "clamp adjust" wiper potential. This clamps A1's input to the "clamp adjust" setting, preventing laser current overdrive. Clamp action need not

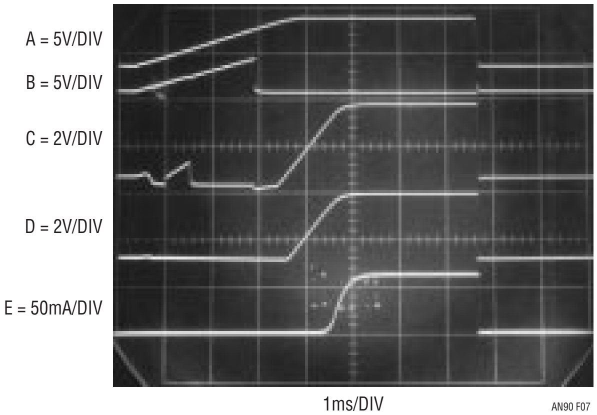

Figure 7. Figure 6's Waveforms During Power Supply Application (Trace A). Traces B and C are LT1431 and A1 Outputs, Respectively. Q1's Emitter (Trace D) Provides Power Gain. Feedback Sets Laser Current (Trace E). Self-Enable Circuit Prevents Spurious A1 Outputs (Trace C) During Supply Ramp Up from Corrupting Laser Current (Trace E)

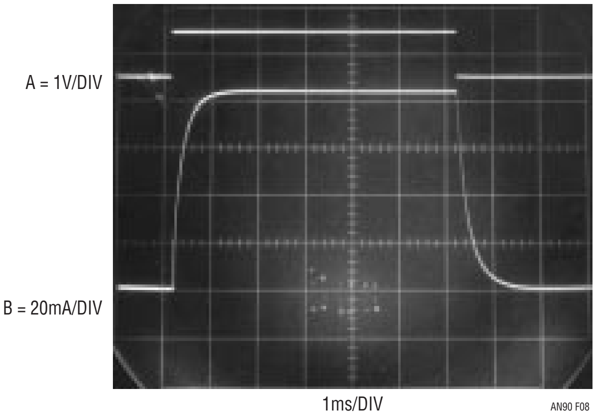

Figure 8. Figure 6's Output (Trace B) Responding to Trace A's Input Step. Trace B's Laser Current Has Controlled Damping, No Overshoot

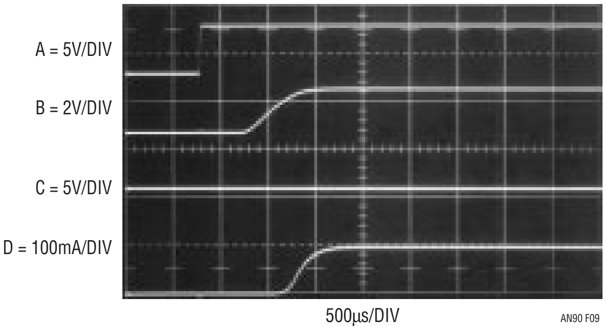

Figure 9. Figure 6's Open Laser Protection Does Not Act During Normal Turn On. Trace A is Supply, Trace B Laser Voltage, Trace C LTC1696 Output and Trace D Laser Current. LTC1696 Overvoltage Threshold is Not Exceeded, SCR is Unbiased (Trace C) and Laser Conducts Current (Trace D)

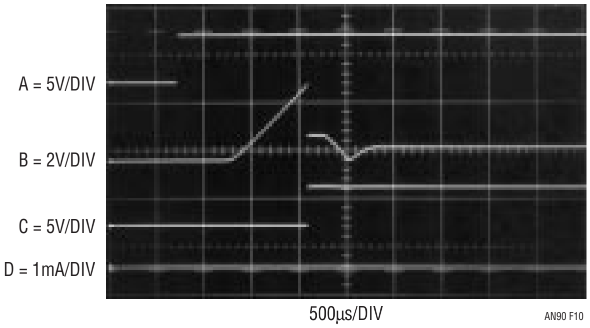

Figure 10. Open Laser Protection Circuit Responding to Open Laser Turn On. Trace Assignments Identical to Previous Figure. Laser Line (Trace B) Excursion Beyond Overvoltage Threshold Causes LTC1696 Output (Trace C), Biasing SCR to Clamp Open Laser Line. No Current Flows in Laser Line, Trace D (Note 100x Increase in Measurement Sensitivity vs Figure 9)

be particularly fast to be effective, because of A1's 10k-0.02µF input filter. Figure 11's traces show clamp response to programming input overdrive. When the programming input (trace A) exceeds the clamp's preset level, Q2's emitter (trace B) does the same, causing A2's output (trace C) to swing down. A2 feedback controls Q2's emitter to the clamp level, arresting the voltage applied to the 10k-0.02µF filter. The filter band limits the abrupt clamp operation, resulting in a smooth corner at A1's positive input (trace D). A1's clamped input dictates a similarly shaped and clamped laser current (trace E). The clamp remains active until the programming input falls below the "clamp adjust" setting.

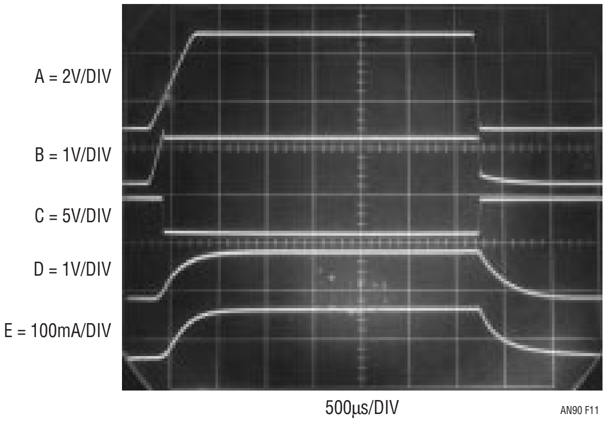

Figure 11. Figure 6's Current Clamp Reacting to Programming Input Overdrive. Waveforms Include Programming Input (Trace A), Q2 Emitter (Trace B), A2 Output (Trace C), A1 + Input (Trace D) and Laser Current (Trace E). When Programming Input Exceeds Clamp Threshold, A2 Swings Abruptly (Trace C), Causing Q2's Emitter (Trace B) to Clamp. A1's +Input (Trace D) Remains at Clamp Level, Maintaining Safe Laser Current (Trace E)

2.5A, Grounded Cathode Current Source

Figure 12, derived from Figures 3 and 6, provides up to 2.5A to a grounded cathode laser. A1 is the control amplifier, output current is efficiently delivered by the LT1506 switching regulator and A2 senses laser current via a 0.1Ω shunt. Loop operation is similar to the descriptions given for Figures 3 and 6 with DC feedback to A1 coming from A2. Frequency compensation differs from the previous figures. Stable loop operation is achieved by local roll off at A1, augmented by two lead networks associated with L1. Midband lead is provided by feeding back a lightly filtered (1k-0.47µF) version of LT1506 V_{SW} output activity. High frequency lead, arriving via the 330Ω-0.05µF pair, optimizes edge response. Figure 13's waveforms detail dynamic response. Trace A's input step arrives in filtered form at A1's positive input (trace B). The loop produces trace C's faithfully profiled laser current output.

As shown, the circuit has the externally controlled enable function, although Figure 6's "self-enable" feature may be used. Similarly, Figure 6's current clamp and open laser protection may be employed in this circuit.

This circuit's switched mode energy delivery provides high efficiency at high power but output noise may be an issue. Residual harmonic content related to switching regulator operation appears in the laser current. The resultant low level modulation of laser output may be troublesome in some applications. Figure 14 shows about 800µA_{P-P} switching regulator related noise in the 2A laser current output.[2] This disturbance is composed of fundamental ripple and switching transition related harmonic. This 0.05% noise is below most optical system requirements, although the following circuit achieves substantially lower noise figures.

0.001% Noise, 2A, Grounded Cathode Current Source

The previous circuit's 0.05% noise content suits many optical system applications. More stringent requirements will benefit from Figure 15's extremely low noise content. This grounded cathode, 2A circuit has only 20µA_{P-P} noise, about 0.001%. Special switching regulator techniques are used to attain this performance. Substantial noise reduction is achieved by limiting edge switching speed in the regulator's power stage.[3] Voltage and current rise times in switches Q1 and Q2 are controlled by the LT1683 pulse width modulator. The LT1683's output stage operates Q1 and Q2 in local loops which sense and control their edge times. Transistor voltage information is fed back via the 4.7pF capacitors; current status is derived from the 0.033Ω shunt and also fed back. This arrangement permits the PWM control chip to fix transistor switching times, regardless of power supply or load changes. The transition rates are set by resistors (R_{VSL} and R_{CSL}) associated with

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Note 2: Noise contains no regularly occurring or coherent components. As such, switching regulator output "noise" is a misnomer. Unfortunately, undesired switching related components in the regulated output are almost always referred to as "noise." Accordingly, although technically incorrect, this publication treats all undesired output signals as "noise." See Reference 7.

Note 3: See Reference 7 for details on this technique.

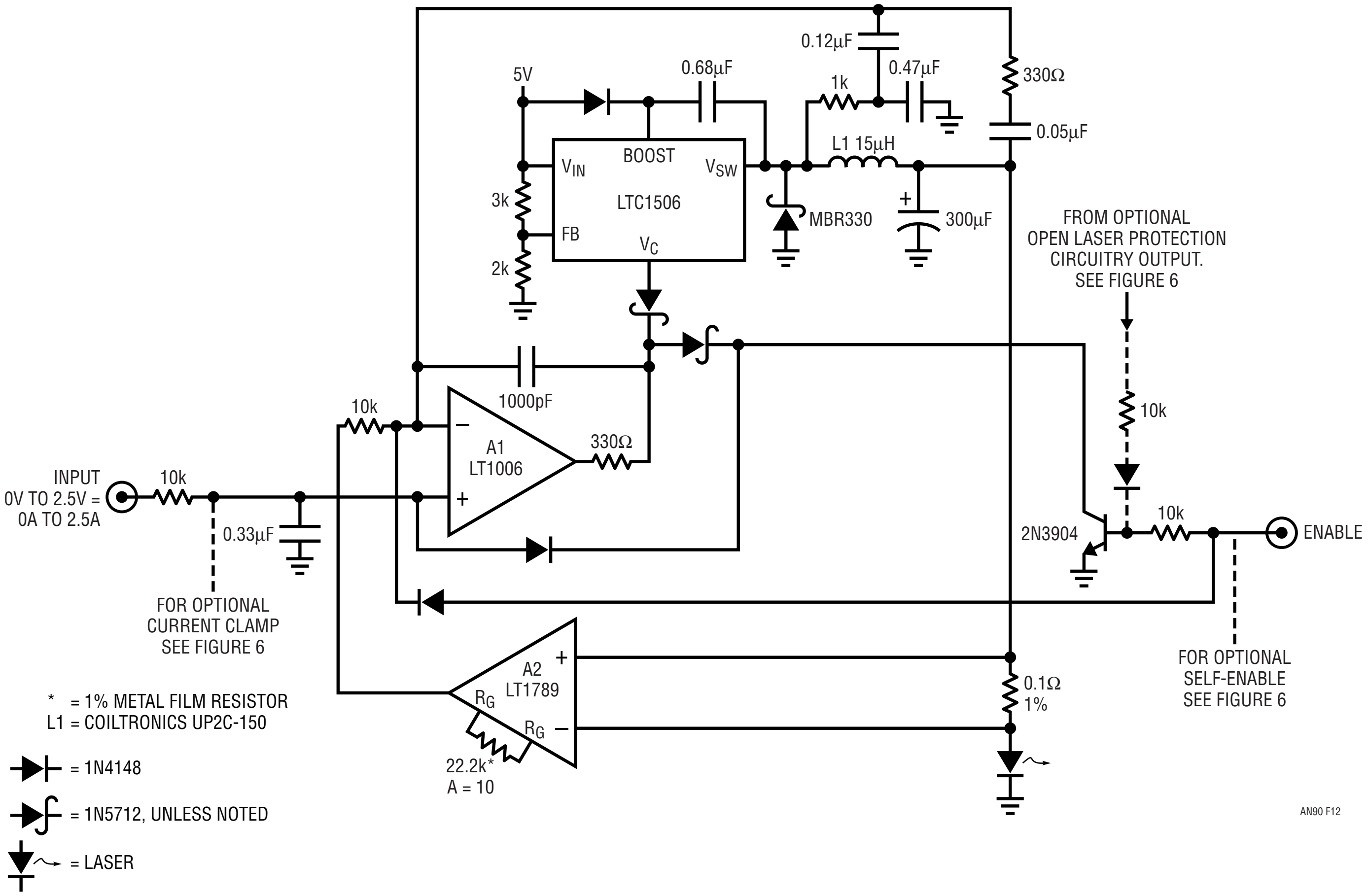

Figure 12. Switched Mode Version of Figure 6 Has 2.5A Output. Feedback Loop Compensation Accomodates Switching Regulator Delay. Clamp, Protection and Self-Enable Circuits are Optional

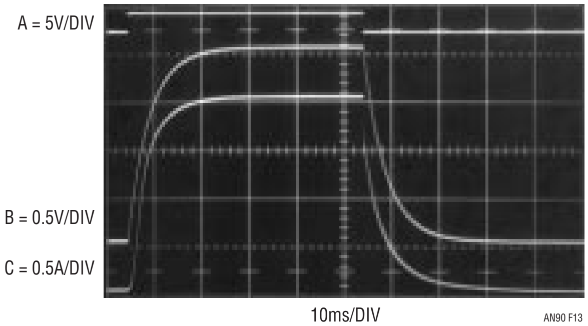

Figure 13. 2.5A Current Source Waveforms for an Input Step (Trace A). A1's Input Filter (Trace B) Smooths Step, Resulting in Trace C's Similarly Shaped Laser Current

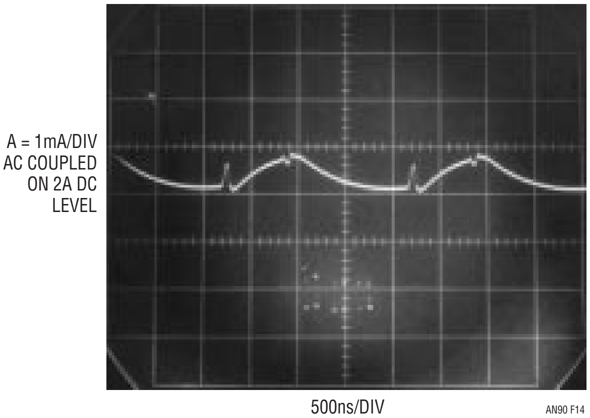

Figure 14. High Power Current Source Noise Includes Switching Regulator Fundamental Ripple and Harmonic Content. 800µA$_{P-P}$ Noise is About 0.05% of 2A DC Output

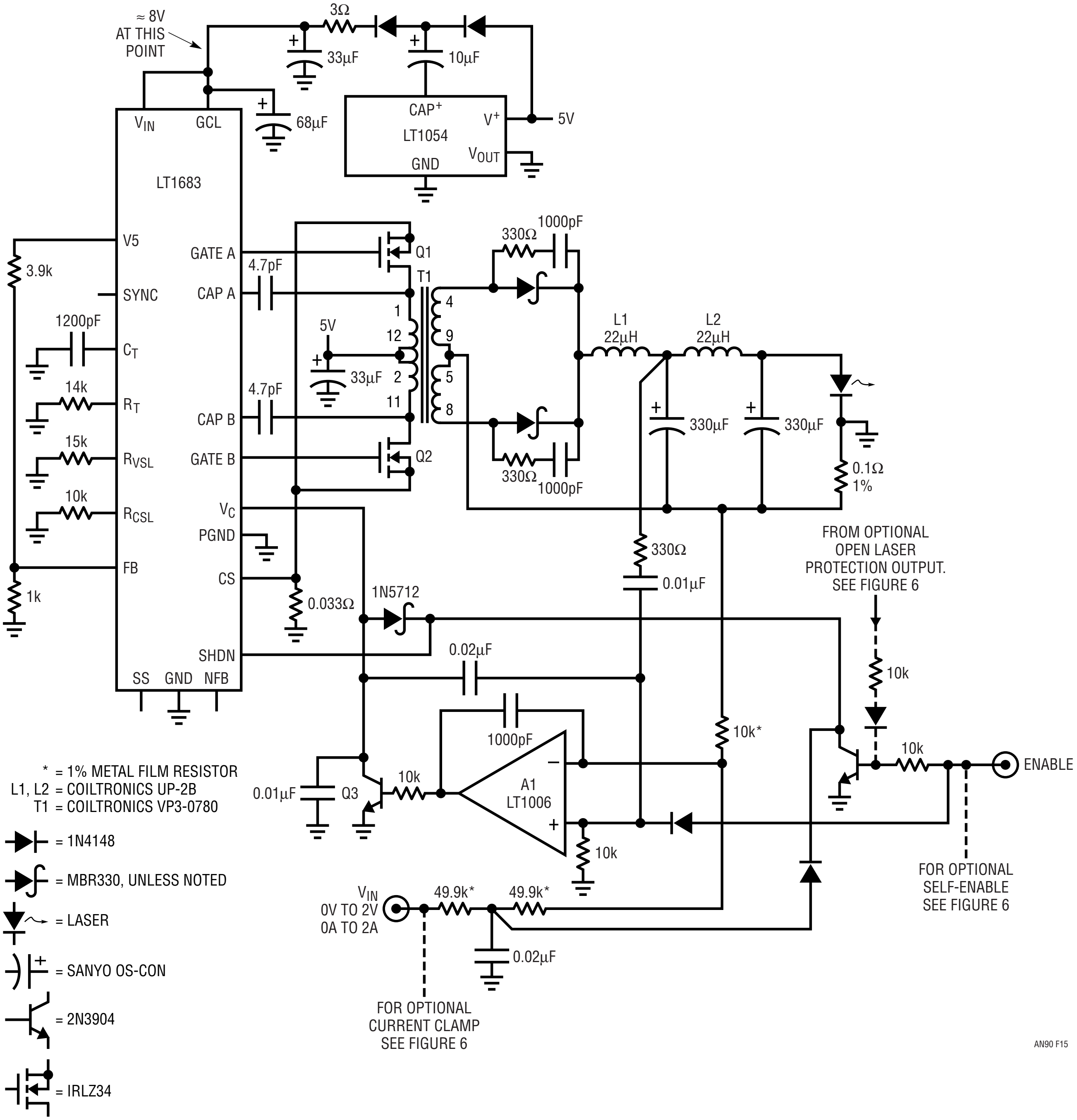

Figure 15. 0.001% Noise, 2A Laser Current Source Has Grounded Cathode Output. Clamp, Protection and Self-Enable Circuits May be Added

the LT1683 controller. In practice, these resistor values are set by adjusting them to minimize output noise. The remainder of the circuit forms a grounded cathode laser current source.

Q1 and Q2 drive T1, whose rectified output is filtered by LC sections. Because T1's secondary floats, the laser cathode and the 0.1Ω shunt may be declared at circuit ground. The shunt is returned to T1's secondary center tap, completing a laser current flow path. This arrangement produces a negative voltage corresponding to laser current at the shunt's ungrounded end. This potential is resistively summed at A1 with the positive voltage current programming input information. A1's output feedback controls the LT1683's pulse width drives to Q1 and Q2 via Q3, closing a loop to set laser current. Loop compensation is set by band limiting at A1 and Q3's collector, aided by a single lead network arriving from the L1-L2 junction.

Some circuit details merit attention. The LT1683's supply input pins are fed from an LT1054 based voltage multiplier. This boosted voltage provides enough gate drive to ensure Q1-Q2 saturation. Damper networks across T1's rectifiers minimize diode switching related events in the output current. Finally, this circuit is compatible with the "self-enable" and laser protection features previously described. Appropriate connection points appear in the figure.

The speed controlled switching times result in a spectacular decrease in noise. Figure 16 shows just 20µA$_{P-P}$ noise, about 0.001% of the 2A DC laser current. Fundamental ripple residue and switching artifacts are visible against the measurement noise floor.[4]

0.0025% Noise, 250mA, Grounded Anode Current Source

This circuit, similar to the previous one, uses edge time control to achieve an exceptionally low noise output. It is intended for lower power lasers requiring grounded anode operation. The LT1533, a version of the previous circuit's LT1683, has internal power switches. These switches drive T1. T1's rectified and filtered secondary produces a negative output, biasing the laser. The laser's anode is grounded and its current path to T1's secondary completed via the 1Ω shunt. This configuration makes T1's center tap voltage positive and proportional to laser current. This voltage is compared by A1 to the current programming input. A1 biases Q2, closing a loop around the LT1533. Loop compensation is provided by local bandwidth limiting at A1 and Q2's collector damping and feedback capacitors.

This circuit's 2.5µA$_{P-P}$ noise qualifies it for the most demanding applications. Figure 18 shows residual switching related noise approaching the measurement noise floor.

The enable function operates as previously described. Additionally, this circuit is compatible with Figure 6's "self-enable" and laser protection accessory circuits. Changes necessitated by the grounded anode operation appear on the schematic.

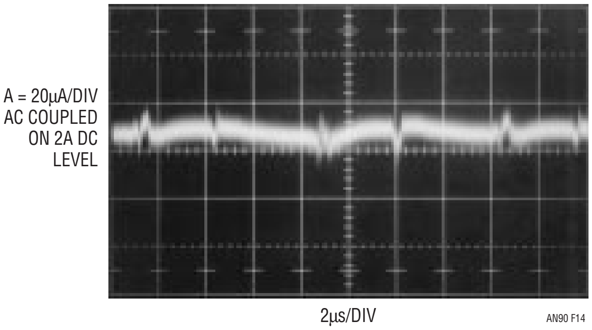

Figure 16. Figure 15's Output Noise Measures ≈20µA$_{P-P}$, About 0.001%. Coherent, Identifiable Components Include Fundamental Ripple Residue and Switching Artifacts

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[4] **Note 4:** Reliable wideband current noise measurement at these levels requires special techniques. See Appedix B, "Verifying Switching Regulator Related Noise" and Appendix C, "Notes on Current Probes and Noise Measurement," for details.

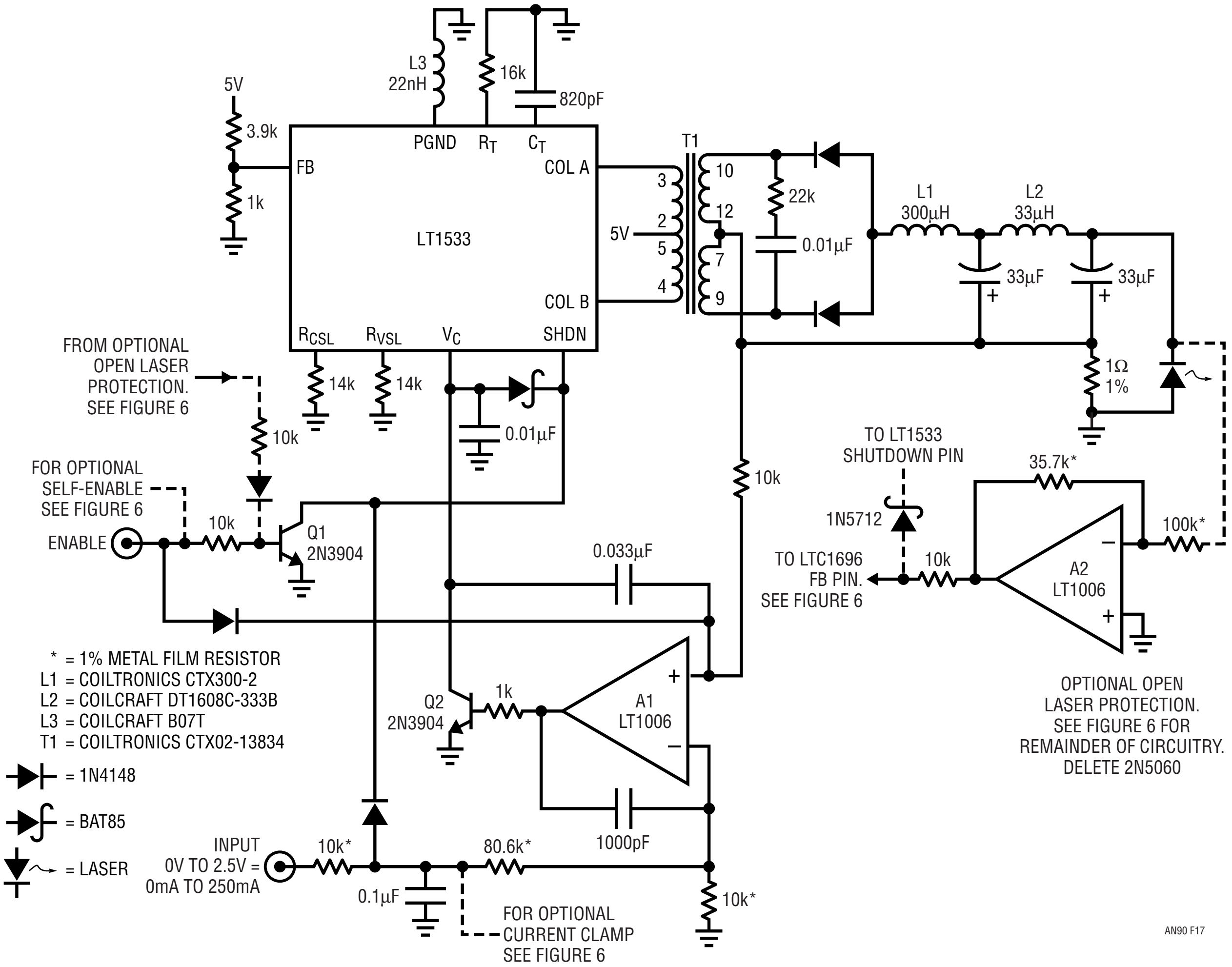

Figure 17. 0.0025% Noise, Grounded Anode Laser Current Source is 250mA Version of Figure 15

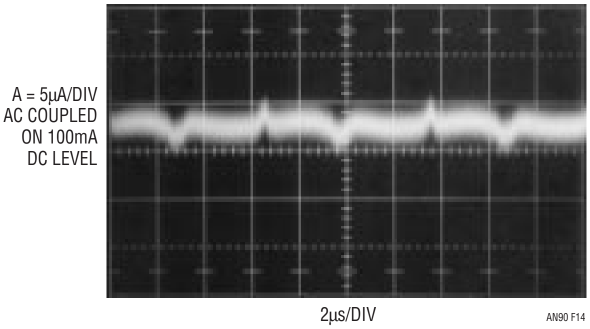

Figure 18. Figure 17's 2.5µA$_{P-P}$ Switching Related Noise is Detectable in Measurement Noise Floor

Low Noise, Fully Floating Output Current Source

Figure 19 retains the preceding example's low noise but also has a fully floating output. Either laser terminal may be grounded without effecting circuit operation. This feature is realized by feedback controlling transformer primary current and relying on interwinding coupling to maintain regulation.[5] This coupling varies slightly with operating point, limiting output current regulation to about 1%.

The schematic shows the LT1533 low noise switching regulator driving T1. The LT1533, while retaining its controlled edge time characteristics, is forced to run at 50% duty cycle by grounding its "duty" pin. Current flows through Q1 and the 0.1Ω shunt into T1's primary. The LT1533 open collector power outputs alternately chop primary current to ground. Primary current magnitude, and hence the 0.1Ω shunt voltage, is set by Q1's bias. Q1's bias, in turn, is set by A1's output, which represents the

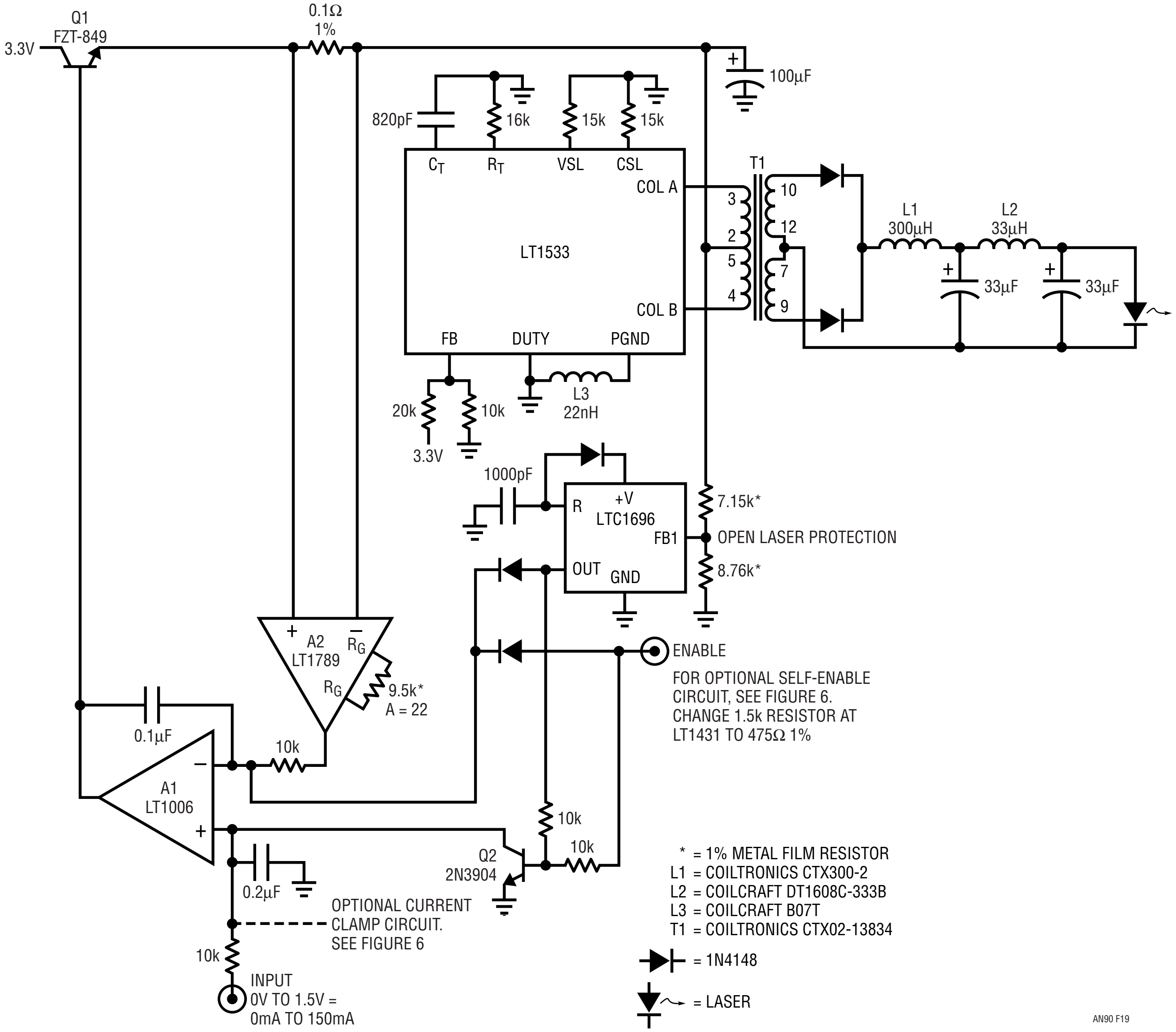

Figure 19. Switched Mode, Low Noise Current Source Has Floating Output, Permitting Grounding Laser Anode or Cathode. Open Laser Protection is Included; Circuit is Compatible with Current Clamp and Self-Enable Options

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[5] **Note 5:** We have engaged this stunt before to serve a variety of purposes. See References 2, 3 and 4.

difference between the output current programming input and A2's amplified version of the shunt voltage. This loop enforces a shunt voltage proportionate to current programming input value. In this way, the current programming input sets T1 primary current, determining T2 secondary current through the laser. Current programming input scaling is calibrated by differential amplifier A2's gain setting resistor.

The primary side feedback's lack of global feedback mandates current regulation compromise. Figure 20's plot of laser current vs programming input voltage shows 1% conformance over nearly the entire range. The error below 10mA, due to nonideal transformer behavior, is normally insignificant because it is below typical laser threshold current. Line regulation, also degraded by the sensing scheme, still maintains about 0.05%/V. Similarly, load regulation, over a 1V to 1.8V compliance voltage, is typically 2%.

This circuit's floating output complicates inclusion of the laser protection and "self-enable" features described in Figure 6's text but they are accommodated. Open laser protection, shown in Figure 20, is accomplished by biasing the LTC1696 from T1's center tap. If the laser opens, the loop forces a marked rise at T1's center tap, latching the LTC1696's output high. This skews A1's inputs, sending its output low and shutting off Q1. All T1 drive ceases. Because the LTC1696 output latches, power must be recycled to reset the circuit. If the laser has not been connected, the latch will act again, protecting the laser from "hot plugging" or intermittent connections. The "self-enable" and current clamp options may be added in accordance with the notations on the schematic.

Anode-at-Supply Current Source

Figure 21's current source is useful where the laser anode is committed to the power supply. A1, sensing Q1's emitter, closes a loop which forces constant current in the laser. Local compensation at A1 and input band limiting stabilize the loop.

This circuit also includes an inherent "self-enable" feature. The LT1635 operates at supply voltages down to 1.2V. Above 1.2V the LT1635's comparator configured section (C1) holds off circuit output until supply voltage reaches 2V. Below 1.2V supply, Q1's base biasing prevents unwanted outputs. Figure 22 details operation during supply turn on. At supply ramp up (trace A), output current (trace D) is disabled. When the supply reaches 2V, C1 (trace B) goes low, permitting A1's output (trace C) to rise. This biases Q1 and laser current flows (trace D). The LT1635 operates on supply voltages as low as 1.2V. Below this level, spurious outputs are prevented by junction stacking and band limiting at Q1's base. Q1's base compo-

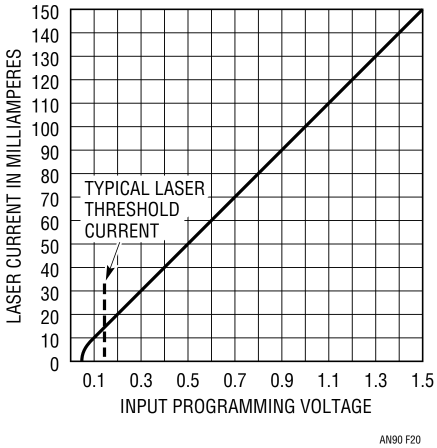

Figure 20. Laser Current vs Input Programming Voltage for Floating Current Source. Conformance is within 1% over Nearly Entire Range. Error Below 10mA, Due to Nonideal Transformer Behavior, is Below Typical Laser Threshold Current

nents also prevent unwanted outputs when the supply rises rapidly. Such rapid rise could cause uncontrolled A1 outputs before the amplifier and its feedback loop are established. Figure 23 shows circuit events during a rapid supply rise. Trace A shows the supply's quick ascent. Trace B, C1's output, responds briefly but goes low some time after the supply moves past 2V. A1 (trace C) produces an uncontrolled output for about 100µs. The RC combination in Q1's base line filters this response to insignificant levels and no laser current (trace D) flows.

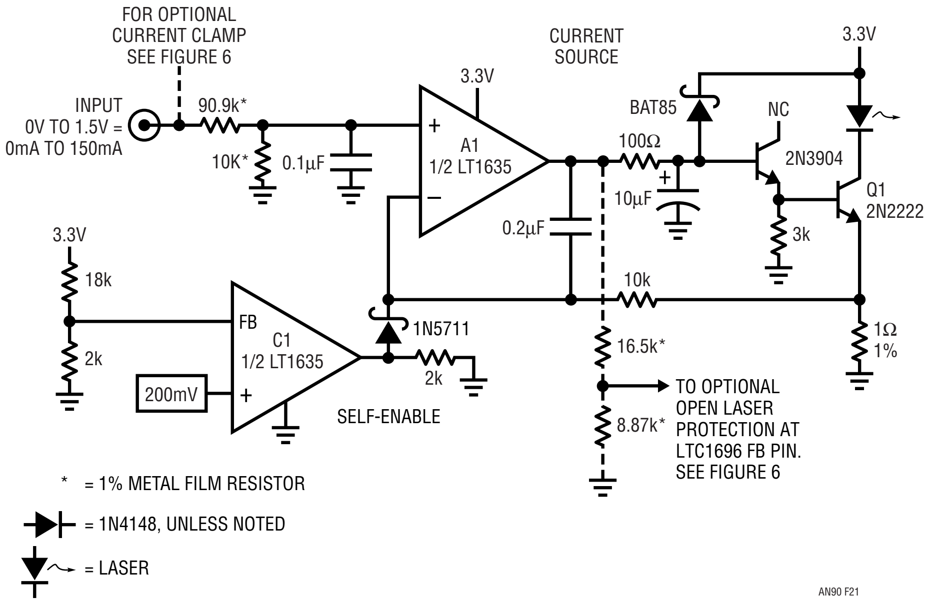

Figure 21. Circuit Has Laser Anode Committed to Supply, Inherent Self-Enabled Operation. LT1635 Functions at 1.2V, Although Self-Enable Feature Holds Off Output Until Power Supply Exceeds 2V. Current Clamp and Open Laser Protection are Optional

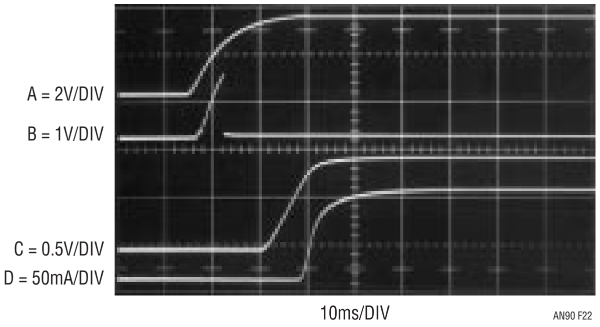

Figure 22. Output Current (Trace D) is Held Off Until Supply (Trace A) Ramps Past 2V. Self-Enable Comparator (Trace B) Operates Above 1.2V; Q1 Base (Trace C) Biasing Prevents Output Below 1.2V

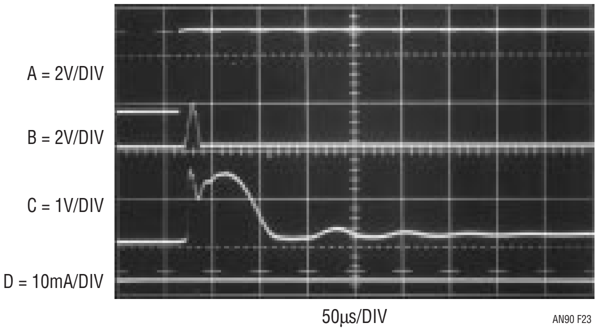

Figure 23. Rapidly Rising Supply (Trace A) Produces No Current Output (Trace D) Despite A1's Transient Uncontrolled Output (Trace C). C1 (Trace B) Reacts Properly but A1's Inactive Loop Cannot Respond. Q1's Base Line Components Preclude Spurious Current Output (Trace D)

The slew retarded input and loop compensation yield clean dynamic response with no overshoot. Figure 24, trace A, is an input step. This step, filtered at A1's input (trace B), is represented as a well controlled laser current output in trace C.

Current clamping and open laser protection options are annotated in the schematic. Additionally, higher output current is possible at increased supply voltages, although Q1's dissipation limits must be respected.

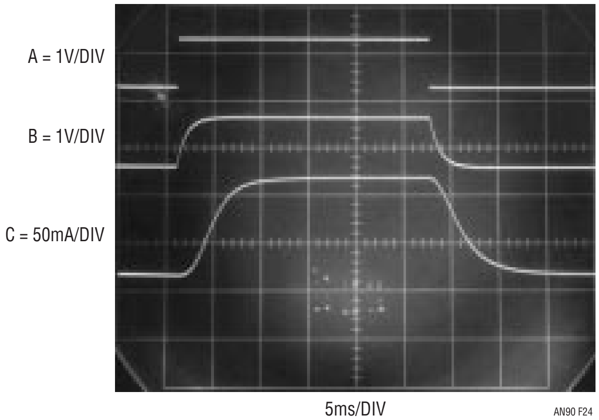

Figure 24. Output Current (Trace C) Responds Cleanly to Filtered Version (Trace B) of Trace A's Input Step

Note: *This application note was derived from a manuscript originally prepared for publication in* EDN *magazine.*

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5. Grafham, D. R., "Using Low Current SCRs," General Electric Co, AN-200.19, January 1967.
6. General Electric Co., "SCR Manual," 1967.
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APPENDIX A

SIMULATING THE LASER LOAD

Fiber optic lasers are a delicate, unforgiving and expensive load. This is a poisonous brew when breadboarding with high likelihood of catastrophe. A much wiser alternative is to simulate the laser load using either diodes or electronic equivalents. Lasers look like junctions with typical forward voltages ranging from 1.2V to 2.5V. The simplest way to simulate a laser is to stack appropriate numbers of diodes in series. Figure A1 lists typical junction voltages at various currents for two popular diode types. The MR750 is suitable for currents in the ampere range, while the 1N4148 serves well at lower currents. Typically, stacking two to three diodes allows simulating the laser in a given current range. Diode voltage tolerances and variations due to temperature and current changes limit accuracy, although results are generally satisfactory.

Electronic Laser Load Simulator

Figure A2 is a laser load simulator powered by a 9V battery. It eliminates diode load junction voltage drop uncertainty. Additionally, any desired "junction drop" voltage may be conveniently set with the indicated potentiometer. Electronic feedback enforces establishment and maintenance of calibrated junction drop equivalents.

The potentiometer sets a voltage at A1's negative input. A1 responds by biasing Q1. Q1's drain voltage controls Q2's base and, hence, Q2's emitter potential. Q2's emitter is fed back to A1, closing a loop around the amplifier. This forces the voltage across Q2 to equal the potentiometer's output voltage under all conditions. The capacitors at A1 and Q1 stabilize the loop and Q2's base resistor and ferrite bead suppress parasitic oscillation. The 1N5400 prevents Q1-Q2 reverse biasing if the load terminals are reversed.

MR750 (25°C)	
TYPICAL JUNCTION CURRENT	TYPICAL JUNCTION VOLTAGE
0.5A	0.68V
1.0A	0.76V
1.5A	0.84V
2.0A	0.90V
2.5A	0.95V

1N4148 (25°C)	
TYPICAL JUNCTION CURRENT	TYPICAL JUNCTION VOLTAGE
0.1A	0.83V
0.2A	0.96V
0.3A	1.08V

Figure A1. Characteristics of Diodes Suitable for Simulating Lasers. Appropriate Series Connections Approximate Laser Forward Voltage

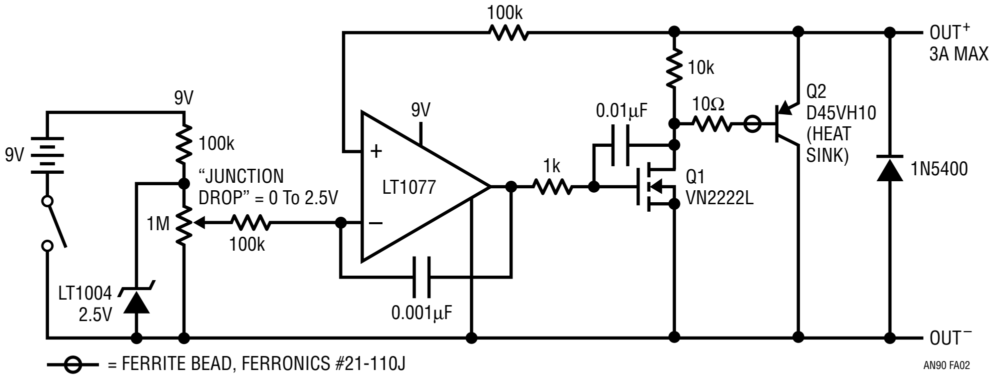

Figure A2. Floating, Battery-Powered Laser Simulator Sets Desired "Junction Drop" Across Output Terminals. Amplifier Feedback Controls Q2's V_{CE} to Potentiometer Voltage

APPENDIX B

VERIFYING SWITCHING REGULATOR RELATED NOISE

Measuring the switching regulator related current noise levels discussed in the text requires care. The microamp amplitudes and wide bandwidth of interest (100MHz) mandates strict attention to measurement technique. In theory, simply measuring voltage drop across a shunt resistor permits current to be determined. In practice, the resultant small voltages and required high frequency fidelity pose problems. Coaxial probing techniques are applicable but probe grounding requirements become severe. The slightest incidence of multiple ground paths ("ground loops") will corrupt the measurement, rendering observed "results" meaningless. Differentially configured coaxial probes offer some relief from ground loop based difficulties but there is an inherently better approach.[1]

Current transformers offer an attractive way to measure noise while eliminating probe grounding concerns. Two types of current probes are available: split core and closed core. The split core "clip on" types are convenient to use but have relatively low gain and a higher noise floor than closed core types.[2] The closed core transformer's gain and noise floor advantages are particularly attractive for wideband, low current measurement.

Figure B1's test setup allows investigation of the closed core transformer's capabilities. The transformer specified has flat gain over a wide bandwidth, a well shielded enclosure and a coaxial 50Ω output connection. Its 5mV/mA output feeds a low noise x100, 50Ω input amplifier. The amplifier's terminated output is monitored by an oscilloscope with a high sensitivity plug-in. A 1V pulse driving a known resistor value ("R") provides a simple way to source calibrated current into the transformer.

If R = 10k, resultant pulsed current is $100\mu A$. Figure B2's oscilloscope photo shows test setup response. The waveform is crisp, essentially noise free and agrees with predicted amplitude. More sensitive measurement involves determining the test setup's noise floor. Figure B3, taken with no current flowing in the transformer, indicates a noise limit of about $10\mu A_{P-P}$. Most of this noise is due to the x100 amplifier.

The preceding exercise determines the test setup's gain and noise performance. This information provides the confidence necessary to make a meaningful low level current measurement. Figure B4, taken with Figure B1's R = 100k, sources only $10\mu A$ to the transformer. This is

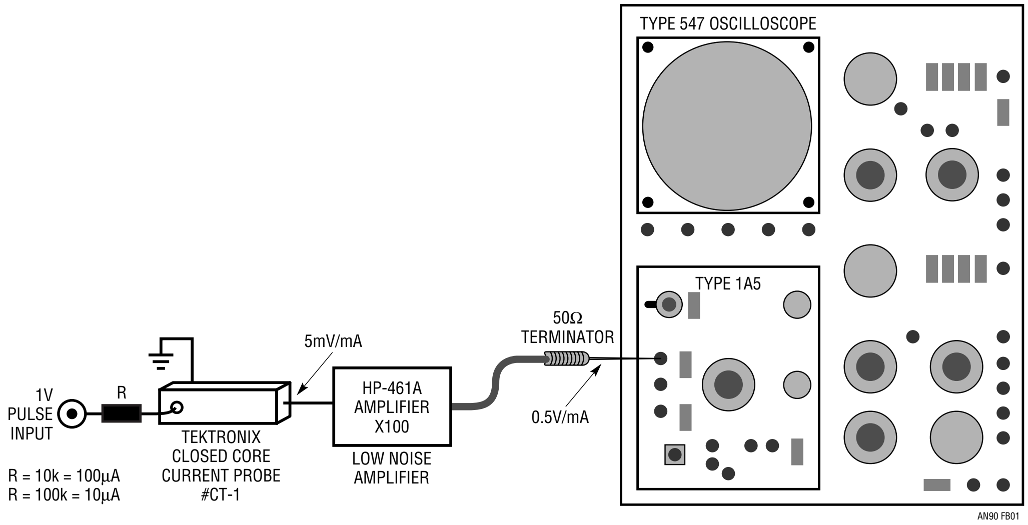

Figure B1. Noise Measurement Instrumentation Includes Resistors, Closed Core Current Probe, Low Noise Wideband Amplifier and Oscilloscope

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[1] **Note 1:** This is not to denigrate low level voltage probing methods. Their practice is well refined and directly applicable in appropriate circumstances. See Appendix C in Reference 7 for tutorial.

[2] **Note 2:** See Appendix C, "Notes on Current Probes and Noise Measurement," for a detailed comparison.

comparable to the previously determined noise floor but the trace, clearly delineated against the noise limit, indicates a 10μA amplitude. This level of agreement qualified this test method to obtain the text's quoted noise figures.

Isolated Trigger Probe

The performance limits noted above were determined with a well defined, pulsed input test signal. Residual switching regulator noise has a much less specific profile. The oscilloscope may encounter problems triggering on an ill-defined, noise laden waveform. Externally triggering the 'scope from the switching regulator's clocking solves this problem but introduces ground loops, corrupting the measurement.[3] It is possible, however, to externally trigger the 'scope without making any galvanic connections to the circuit, eliminating ground loop concerns. This is accomplished by coupling to the field produced by the switching regulator magnetics. A probe which does this is simply an RF choke terminated against ringing (Figure B5). The choke, appropriately positioned, picks up residual switching frequency related magnetic field, generating an isolated trigger signal.[4] This arrangement furnishes a 'scope trigger signal with essentially no measurement corruption. The probe's physical form appears in Figure B6. For good results, the termination should be adjusted for minimum ringing while preserving the highest possible amplitude output. Light compensatory damping produces Figure B7's output, which will cause poor 'scope triggering. Proper adjustment results in a more favorable output (Figure B8), characterized by minimal ringing and well defined edges.

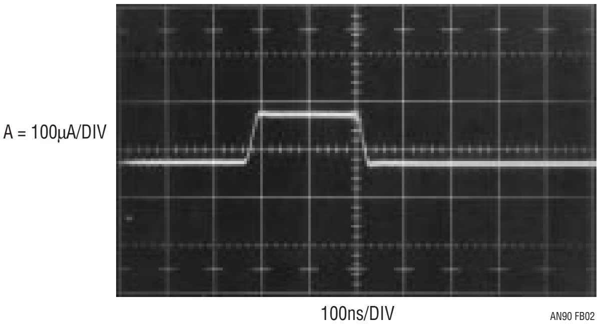

Figure B2. Response to a 100μA Input is Clean. Displayed Amplitude Agrees with Input Stimulus, Indicating Calibrated Measurement

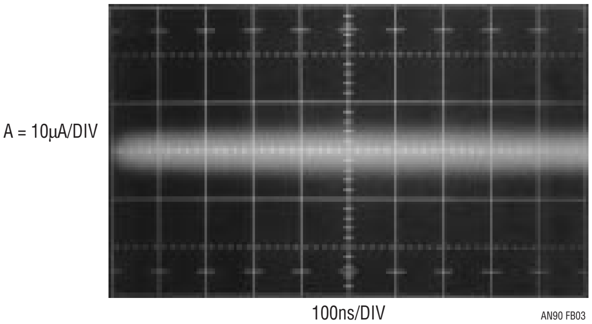

Figure B3. 10μA Noise Floor is Determined by Removing Current Loop from Transformer. Remaining Noise is Primarily Due to x100 Amplifier

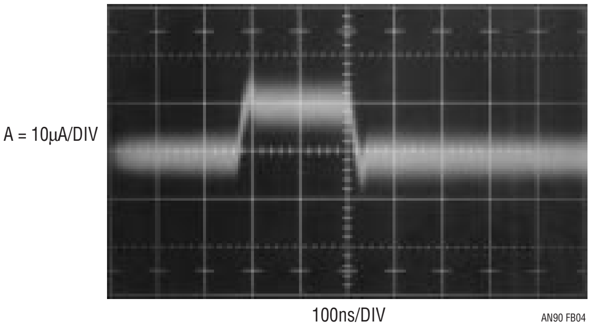

Figure B4. Verifying Gain Near Noise Floor. 10μA Input Pulse Produces Calibrated, Readily Discernable Output

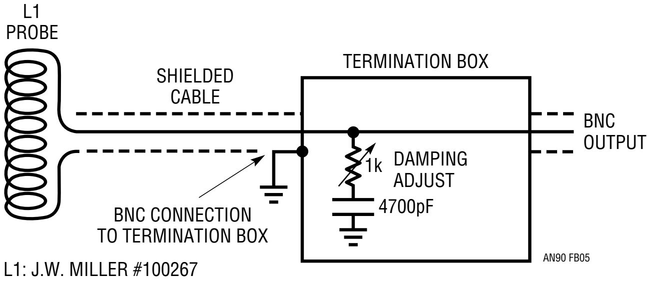

Figure B5. Simple Trigger Probe Eliminates Board Level Ground Loops. Termination Box Components Damp L1's Ringing Response

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[3] **Note 3:** See previous comments at the beginning of this appendix.

[4] **Note 4:** Veterans of LTC application notes, a hardened crew, will recognize this probe's description from LTC Application Note 70 (Reference 7). It directly applies to this topic and is reproduced here for reader convenience.

Trigger Probe Amplifier

The field around the switching magnetics is small and may not be adequate to reliably trigger some oscilloscopes. In such cases, Figure B9's trigger probe amplifier is useful. It uses an adaptive triggering scheme to compensate for variations in probe output amplitude. A stable 5V trigger output is maintained over a 50:1 probe output range. A1, operating at a gain of 100, provides wideband AC gain. The output of this stage biases a 2-way peak detector (Q1 through Q4). The maximum peak is stored in Q2's emitter capacitor, while the minimum excursion is retained in Q4's emitter capacitor. The DC value of the midpoint of A1's output signal appears at the junction of the 500pF capacitor and the 3MΩ units. This point always sits midway between the signal's excursions, regardless of absolute amplitude. This signal-adaptive voltage is buffered by A2 to set the trigger voltage at the LT1394's positive input. The LT1394's negative input is biased directly from A1's output. The LT1394's output, the circuit's trigger output, is unaffected by >50:1 signal amplitude variations. An x100 analog output is available at A1.

Figure B10 shows the circuit's digital output (trace B) responding to the amplified probe signal at A1 (trace A).

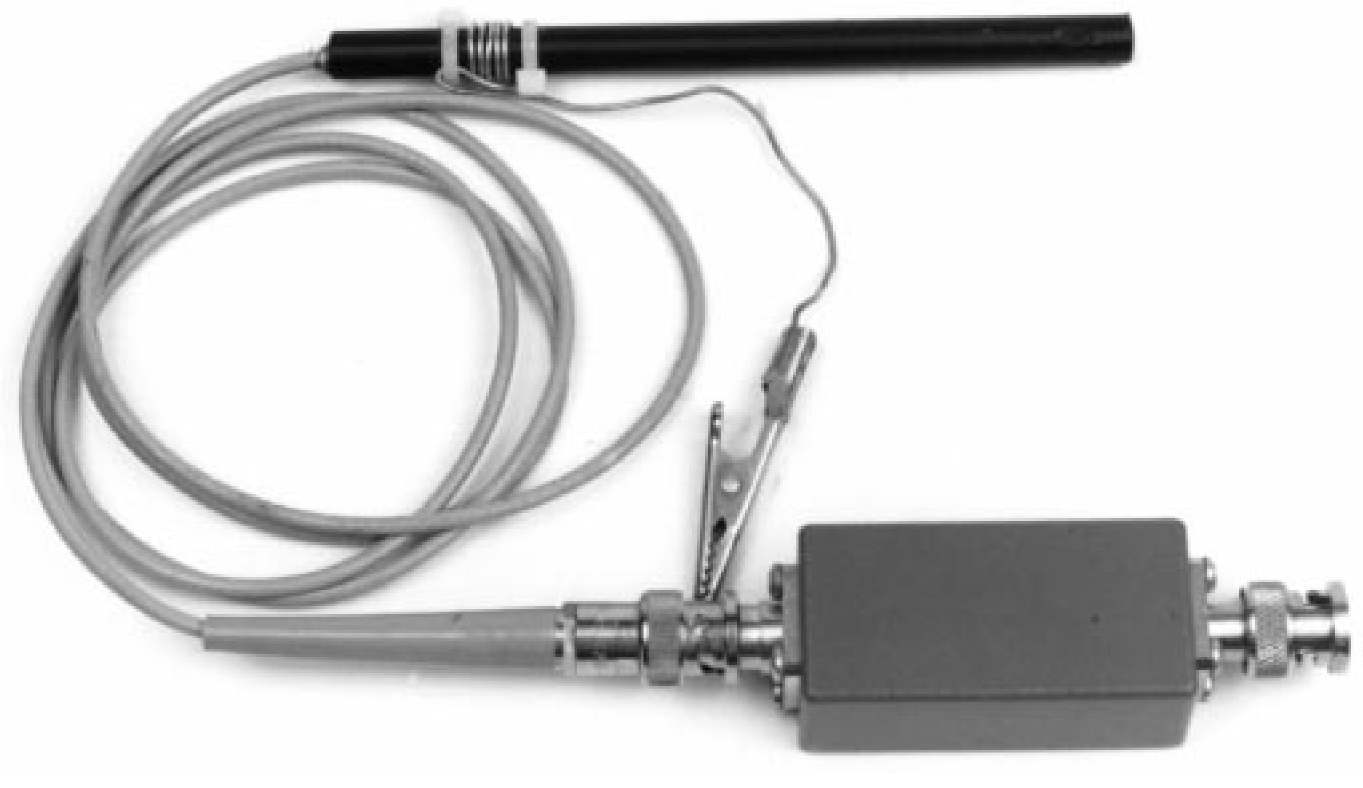

Figure B6. The Trigger Probe and Termination Box. Clip Lead Facilitates Positioning Probe, is Electrically Neutral

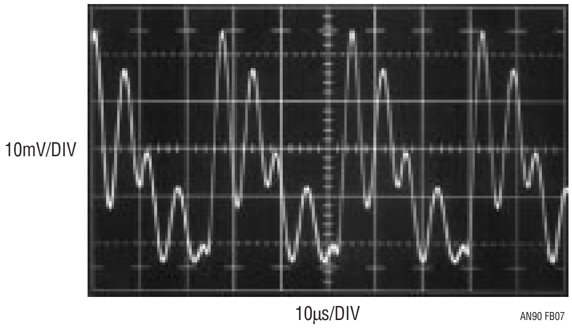

Figure B7. Misadjusted Termination Causes Inadequate Damping. Unstable Oscilloscope Triggering May Result

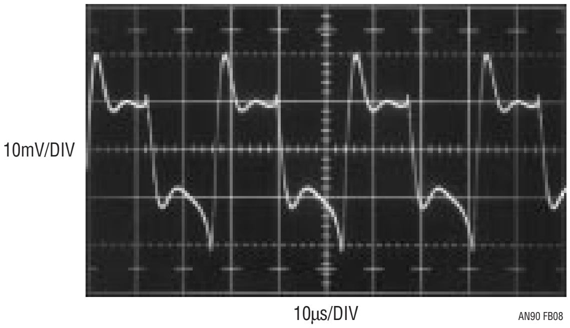

Figure B8. Properly Adjusted Termination Minimizes Ringing with Small Amplitude Penalty

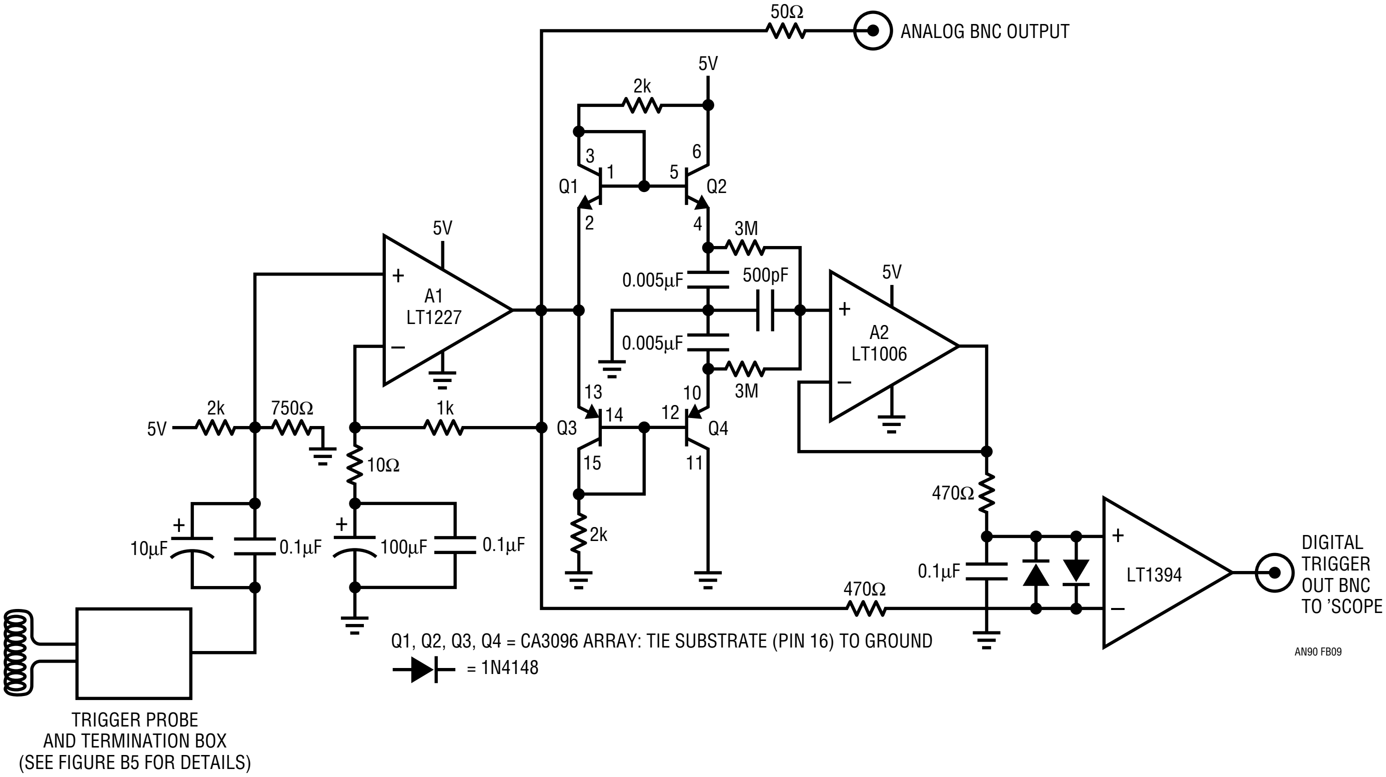

Figure B9. Trigger Probe Amplifier Has Analog and Digital Outputs. Adaptive Threshold Maintains Digital Output over 50:1 Probe Signal Variations

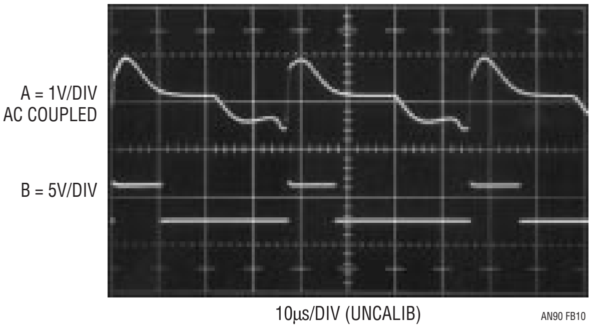

Figure B10. Trigger Probe Amplifier Analog (Trace A) and Digital (Trace B) Outputs

APPENDIX C

NOTES ON CURRENT PROBES AND NOISE MEASUREMENT

Appendix B explained current probes advantages in switching regulator related current noise measurement. Their minimally invasive nature eases connection parasitics, enhancing measurement fidelity. Different combinations of current probes and amplifiers provide varying degrees of performance and convenience. Figure C1 summarizes characteristics for two probes and applicable amplifiers. In general, the noise floor uncertainties of the convenient split core types are compromised by their construction. The closed core probes are less noisy and some types have inherently higher gain, a distinct advantage. A laboratory based comparison is revealing.

Figure C2 shows the CT-1 (closed core)-HP461A combination responding to a 100µA pulsed input. The waveform is clearly outlined, with pulse top and bottom trace thickening deriving from the noise floor.[1] Figure C3, taken with the same input, is degraded. The split core P6022-Preamble 1855 combination used has much greater noise. The decreased performance is almost entirely due to the split core probe's construction.

In closing, it is worthwhile noting that Hall element stabilized current probes (e.g., Tektronix AM503, P6042) are not suitable for low level measurement. The Hall device based flux nulling loop extends probe response to DC but introduces ≈300µA of noise.

CURRENT PROBE	AMPLIFIER	NOISE FLOOR (100 MHz BW)	COMMENTS
Tektronix P6022 (1mV/mA)	Preamble 1855 (1MΩ)	100µA	Split Core is Convenient to Use but Sensitivity is Low, Resulting in Relatively High Overall Noise Floor
Tektronix CT-1 (5mV/mA)	Hewlett-Packard 461A (50Ω)	15µA	Probe's Higher Gain Accounts for Most Noise Floor Reduction—50Ω Input Amplifier Provides Some Additional Benefit. Closed Core Probe Requires Breaking Conductor to Make Measurement

Figure C1. Recommended Instrumentation for Current Noise Measurement. Split Core "Current Probe" is Convenient; Closed Core Provides Higher Gain and Lower Noise

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[1] **Note 1:** Diehard curmudgeons still using high quality analog oscillscopes routinely discern noise presence due to trace thickening. Those stuck with modern instruments routinely view thick, noisy traces.

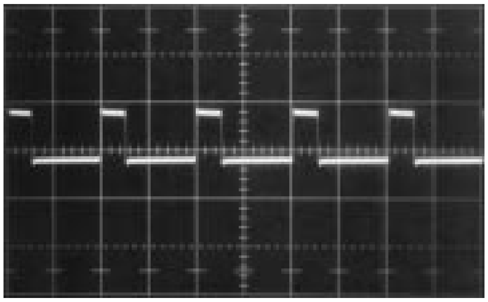


Figure C2. CT-1/HP-461A Combination Clearly Displays a 100μA Pulse Train. Noise Floor Causes Slight Pulse Top and Bottom Trace Thickening

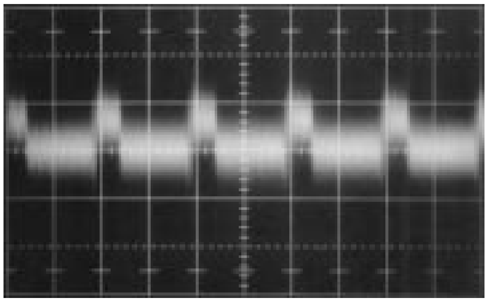
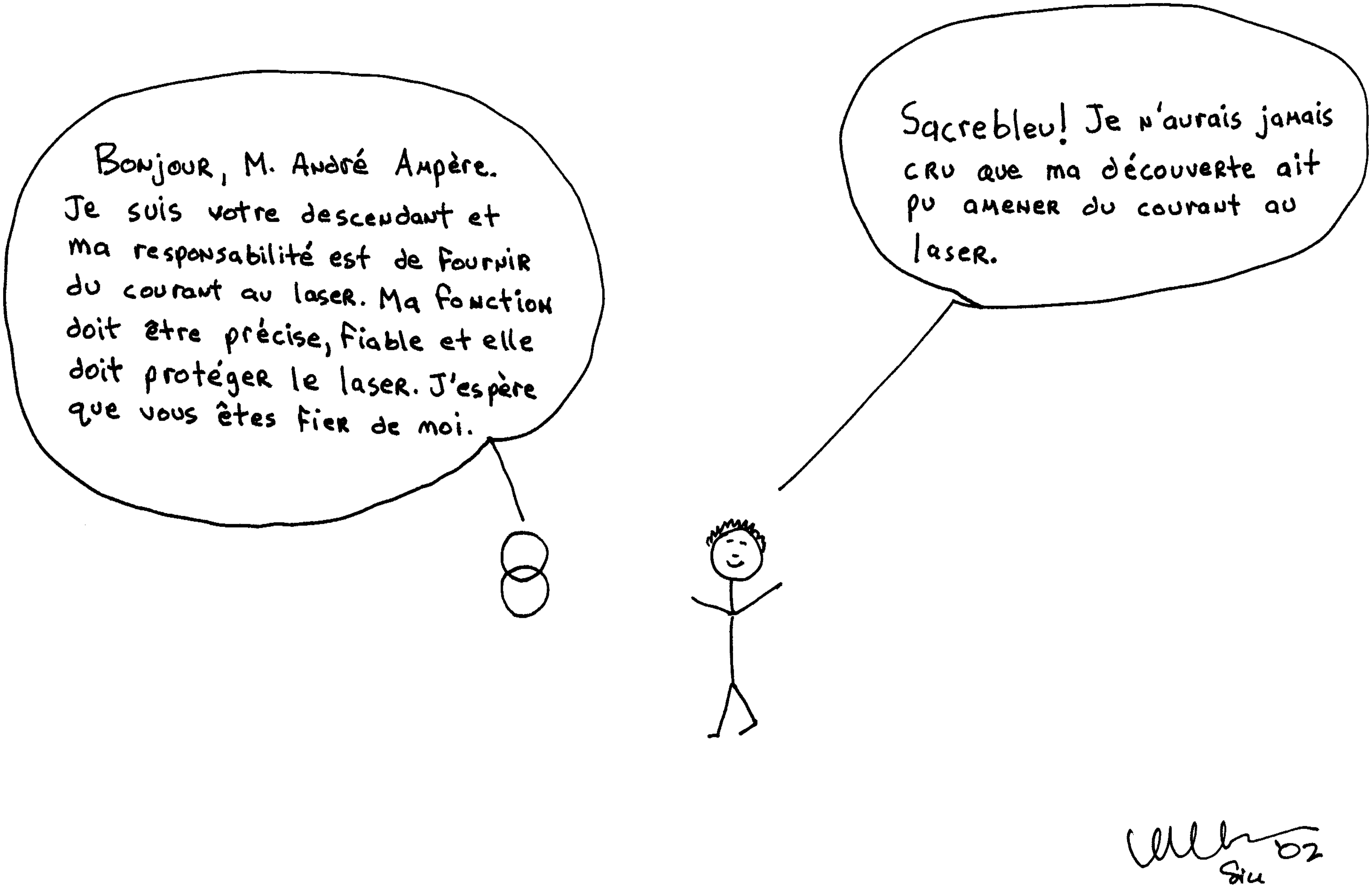


Figure C3. P6022/Preamble 1855 Presentation of Previous Figure's Waveform Has Degraded Signal-to-Noise Performance. Split Core "Current Probe" Convenience Necessitates Measurement Fidelity Compromise



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