Improve Laser Diode Performance by Reducing Output Cable Inductance using Twisted Pair Cable

By

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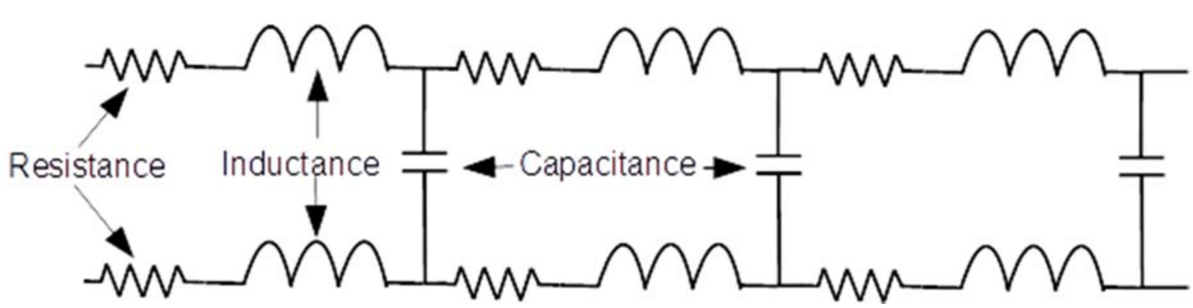
The intent of this article is to provide information regarding the performance of twisted pair cable to reduce output cable inductance. The information is based in electromagnetic theory and is supported with actual measured results which apply to a subset of laser diode applications.

Introduction and scope

Frustration in the laser lab reaches an all-time high as two consecutive fire-cracker-like explosions are heard. A brief orange flame appears followed by an acrid-smelling, eye-watering greenish-gray smoke which heads directly toward the smoke detectors in the ceiling above. The five thousand-dollar once shiny pristine gold colored laser now takes on a dingy brown smoke-smudged appearance. As if this weren't bad enough, the big, big boss arrives just in time to see the last of the now-liquid low-melt solder ooze from the laser stack and splash to the floor like rain drops on hot pavement. My mind races with questions like: Is it the control system? Why was the output so erratic just before the meltdown? Did we overlook something during the initial installation? High expectations are now dashed, customer commitments must be re-negotiated and schedules delayed. No one has a satisfactory answer as to the root cause of the failure. Cable connections are checked and re-checked. Unsuspecting equipment suppliers are implicated. Calls are made to return pieces of not-proven-but suspect equipment. We frantically re-boot control panels and computers to no avail. All the while the root-cause of the failure is lying silent-but-deadly within the output cable. Who can imagine that this seemingly insignificant part of the laser system can cause so much destruction? In fact, often the output cable and its connections to the load contain the most overlooked problem source in the whole system. Symptoms of poor cable performance are often manifested in anything from unexplained fluctuations in laser output intensity to permanent laser damage. But the question often asked is, why should I suspect the output cable when there are no signs of overheating or visible damage on the insulated wire? The answer is that although there are several properties of the output cable to consider, the main culprit is output cable inductance. Inductance doesn't make a sound and is completely invisible but can wreak havoc in the output circuit and even destroy a laser diode. This is the silent-but-deadly part. Although this was just a story, it could be your story. In the following paragraphs I describe the basic problem with output cable inductance and explain how the twisted pair cable can provide a solution. In support of this solution, an example experiment is included complete with actual measured test results.

Just as the name implies, twisted pair cable is comprised of two identical wires tightly twisted together. This style of cable has been around since Alexander Graham Bell invented it in 1881. It does have limitations, but can be very effective for square-wave pulses having greater than 100 ns rise and fall times. In general, the purpose of the output cable is to transfer the electrical energy from the power source to the load. The typical output cable is comprised of resistance, capacitance and inductance. It is generally modeled as the circuit shown in figure 1 below.

Figure 1. Equivalent circuit model of output cable



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In this discussion, *only* the inductive component is addressed as it is generally the least understood and has the greatest impact on cable performance. The power source in this case is a pulsed current source and the load is a laser diode. The output of the pulsed current source is basically a square wave and because of its pulsed nature, provides abrupt changes in power to the load. The laser diode load, due to the diode-switch-like characteristics, provides another source of abrupt changes. Abrupt changes in source and load are part of the ingredients that enhance the detrimental characteristics of cable inductance. Minimizing the cable inductance in this pulsed environment is especially important. Twisted pair cable can minimize unwanted inductance, and as a result, greatly improve laser diode performance. For the sake of this discussion, assume that an appropriately-sized twisted pair two-wire system has been chosen and the rise and fall times are no less than 1 us. A basic block diagram representation is shown in figure 2 below.

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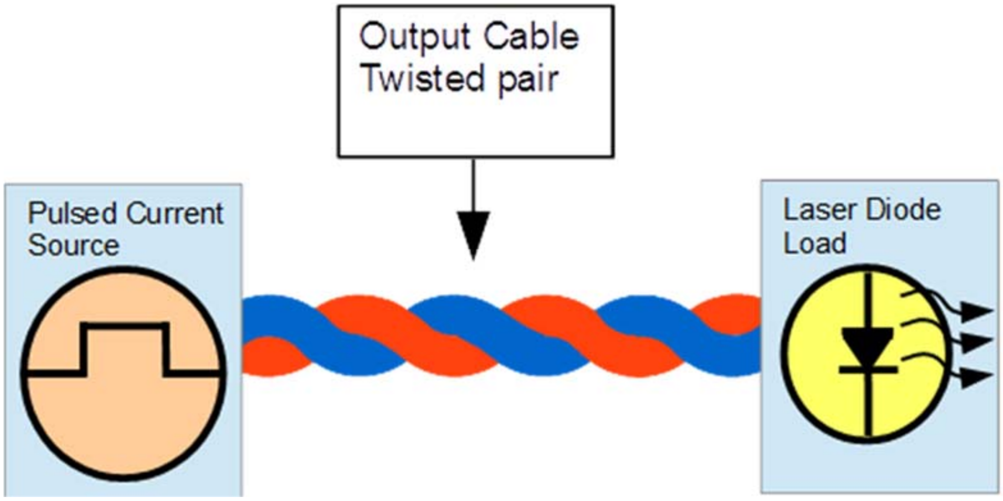
Figure 2.



Inductance and related electromagnetic theory

In order to understand the twisted pair solution it is necessary to develop a more detailed understanding of inductance. What is inductance? Most electronics students are taught that inductance is the measure of the ability of a device to store energy in and through an electromagnetic field. Although true, this doesn't provide the level of detail needed to understand the role inductance plays in the physical construct of a twisted pair output cable. To gain a more practical understanding, it is necessary to describe the following situation. Refer to figure 3 below as directed throughout the explanation.

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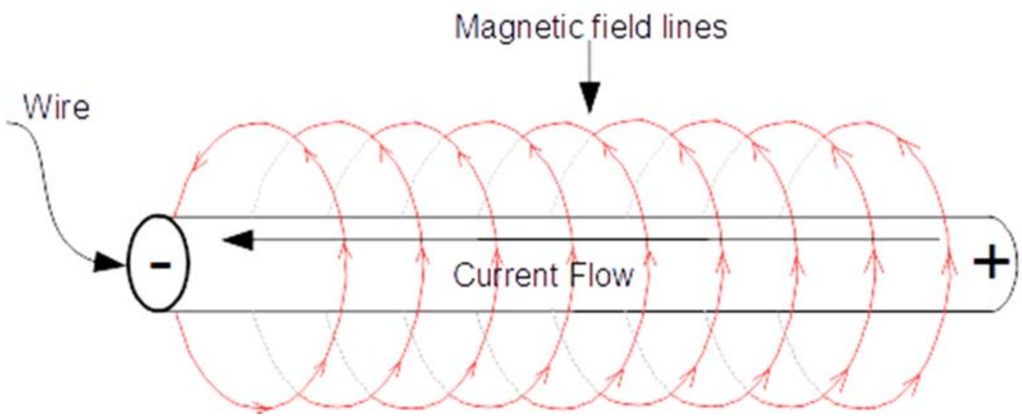
Figure 3.



Any time current flows through a wire, a quantity of concentric circular magnetic field lines are created around that wire. These magnetic field lines have qualities of both magnitude and direction. The magnitude is directly proportional to the amplitude of current flow in the wire. The direction of the magnetic field lines can be determined by applying the right hand rule for current flow. Simply place the right-hand palm around the wire with the thumb pointed in the conventional direction of current flow. As a result the right-hand fingers will naturally wrap in the direction of the magnetic field lines. Notice the example in figure 3 above. The red arrows indicate magnetic field line direction. The number of field lines are counted in units called webers. A weber is a certain quantity of field lines. One weber per ampere constitutes one henry. Inductance is measured in henrys. Therefore, inductance in a wire is the quantity of field lines in webers per the amperes required to create those field lines. This relationship can be mathematically expressed as follows:

$L = \frac{N}{I}$ or rearranged as, (1)

$N = LxI$ where,

$N =$ a quantity or number of field lines in webers

$L =$ inductance in henrys

$I =$ current in amperes

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Basically, any time current flows through a wire, a directly proportional amount of magnetic field lines will appear around that wire. This situation results in a quantity of inductance. For any current, the longer the wire length the more field lines are created and therefore the greater the inductance value. Conversely, when the wire is short fewer magnetic field lines are created. The result is less inductance.

Another quality associated with these magnetic field lines is that any change in the number of field lines will result in a corresponding voltage created across that wire. The amount of voltage created is directly proportional to how quickly the number of field lines change. As mentioned before, any abrupt change in source and or load essentially causes the number of field lines to quickly change and create this detrimental voltage. This created voltage is sometimes called switching noise, change in current noise and ground bounce. This relationship can be expressed mathematically as follows:

$V = \frac{\Delta N}{\Delta T}$ or if rearranged as,

$\Delta N = V x \Delta T$ where, (2)

$V =$ the amplitude of the created voltage

$\Delta N =$ change in quantity or number of field lines in webers

$\Delta T =$ change in time measured in seconds

At this point the relationship between the number or quantity of field lines to current I, inductance L **and** the number of field lines to the created voltage V has been expressed. Therefore it is now possible to combine them into the following single mathematical expression.

Since $N = LxI$ then, $\Delta N = Lx\Delta I$ and $\Delta N = Vx\Delta T$ therefore,

$Lx\Delta I = Vx\Delta T$ which can be rearranged as;

$$V = L\frac{\Delta I}{\Delta T} \quad (3)$$

Direct application to twisted pair cable

As evident in the formula (3) above, inductance L is directly proportional to the created voltage V . Reducing inductance reduces the created voltage V. Depending on the amount of inductance and change in current involved, this created voltage can easily achieve values in excess of the applied circuit voltage. Depending on circuit conditions this created voltage V can exceed the laser diode breakdown voltage and permanently damage the laser diode. In this situation, reducing cable inductance is an absolute necessity.

Now, when applying this information to a representative portion of the actual circuit, refer to figure 4 below. Notice the output cable is comprised of two identical wires, a positive output wire and a return wire. In this case, the current in the positive output wire is equal to the current in the return wire. Current will flow from the positive output wire to the laser diode load, through the laser diode load and through the return wire. The resulting magnetic field lines on both wires will appear as shown. Notice the directional arrows in the field lines of the positive output wire are exactly opposite those indicated in the return wire. This fact is fundamental to the twisted pair solution. Although the magnetic field lines in figure 4 are represented by single concentric circles, they might be better visualized as gradient planes of magnetic field perpendicular to the wire itself. The magnetic field is most dense near the wire and diminishes in intensity as it expands perpendicularly, outward away from the wire. More specifically, the intensity of this magnetic field tends to diminish with the square of the distance from the wire.

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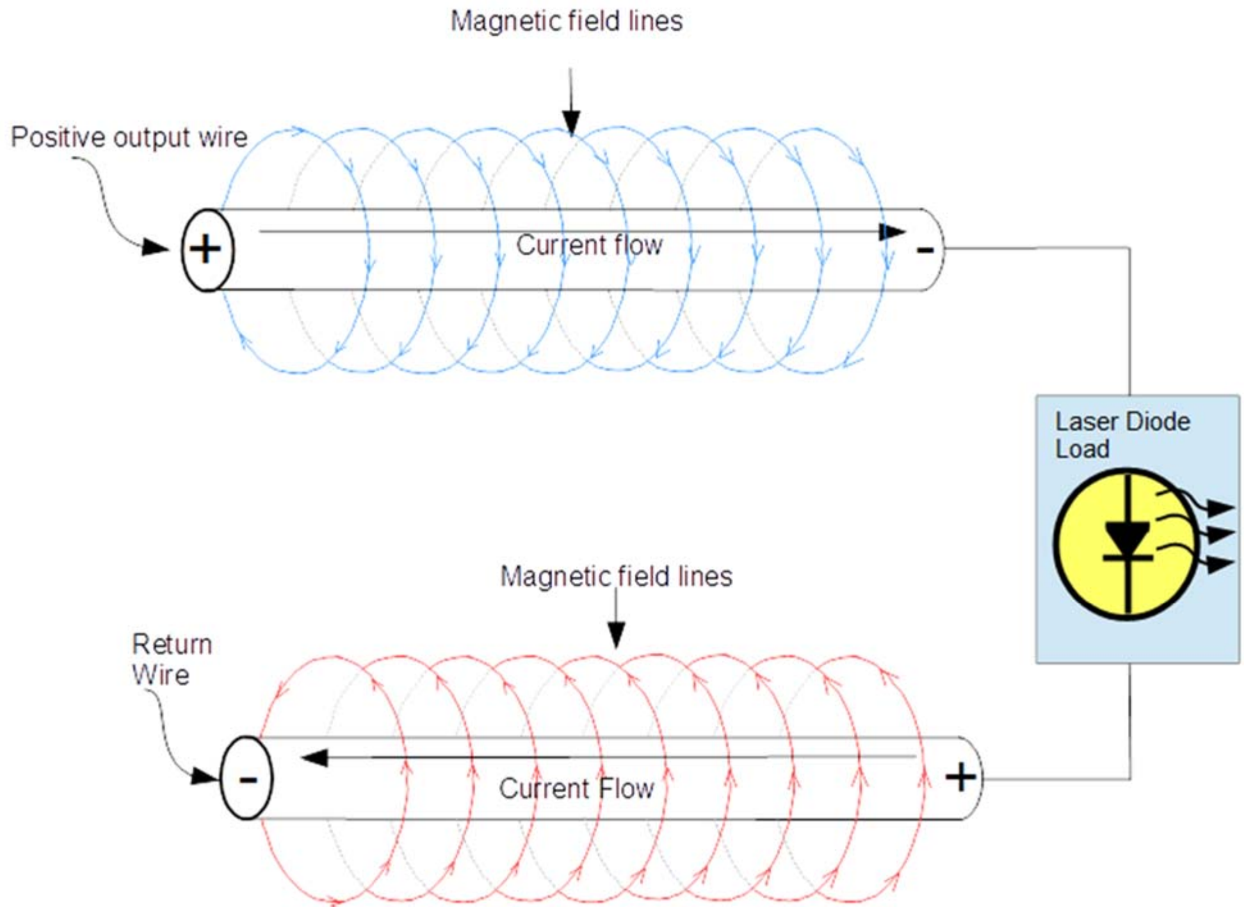
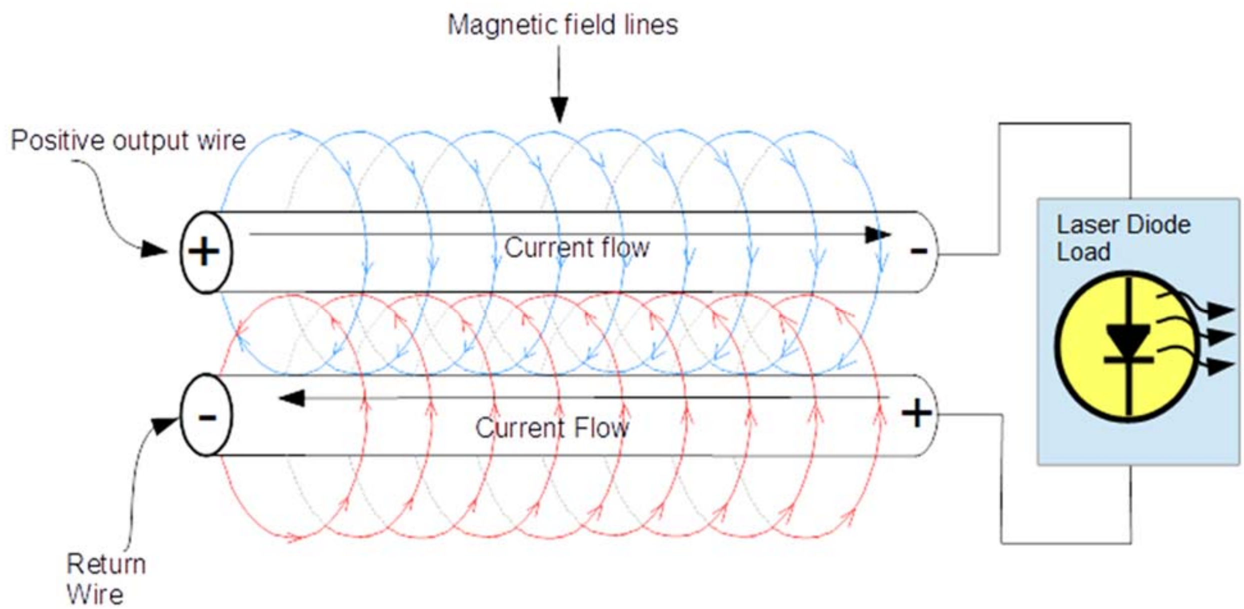
Figure 4.



Consider what will happen if the positive output wire and the return wire are placed next to each other lengthwise. Refer to figure 5 below. Since their magnetic field lines are in opposition to each other in both magnitude and direction, they will tend to cancel or effectively reduce the overall number of field lines surrounding each of the wires via mutual coupling. It is important to notice that only a portion of the magnetic field lines will be cancelled in each wire and therefore some net inductance will remain. The effect is that overall inductance will decrease. Minimum overall inductance occurs when the wires are placed as close as possible to each other. In fact, if it were possible for the positive output wire to physically occupy the same space as the return wire, then theoretically the field lines of each wire would completely negate the other effectively eliminating all inductance between these two wires. Of course this is not possible, but the essential relationship remains true. The main principle to remember is increasing the distance between the wires increases the overall inductance, and reducing the distance between the wires reduces the overall inductance. In addition, it is very important that the currents in both the positive output wire and the return wire be the same. Any difference in the two currents will increase the overall number of field lines and therefore increase inductance rather than reduce it. It is these fundamental characteristics of cable inductance that make the twisted-pair solution effective.

Figure 5.



Twisting a pair of identical wires together positions both wires as close as possible to each other. Essentially the output cable's inductance is used against itself. Since the return wire is effectively looped back and inter-twisted with the positive output wire, maximum magnetic field line cancellations occur and minimum inductance is achieved. Due to the tight mutual coupling of the wires any outside radiated or conducted signal will be experienced by both wires and significantly cancelled. Essentially, this creates a common mode situation providing a level of noise immunity from outside sources.

Ideally, only the true differential current pulse is transferred from the source to the laser diode load. In addition, a tightly-twisted pair of identical wires creates a more predictable and uniform characteristic cable impedance. The result is an increase in the uniform capacitance between the wires.

Summary of twisted pair cable inductance as it applies to laser diodes

In summary, twisted pair cable takes advantage of these four basic principles of reducing inductance:

1. The direction of the magnetic field lines in the output wire and the return wire must be opposite. (Refer to the right hand rule for conventional current flow to make this determination.)
2. The current in both the output wire and the return wire must be identical in amplitude and wave shape. Any differences in wave shape and or amplitude will result in less cancellation of the magnetic field lines, which will effectively increase overall inductance.
3. For maximum magnetic field line cancellation, the output wire and the return wire must be physically identical and placed as close as possible to each other. The twisted pair solution maximizes this principle.
4. The overall output cable wires must be as short as possible. Any unnecessary length will result in an increase of overall cable inductance.

Properly applied, the twisted pair solution employs aspects of all four principles listed above. The result is less inductance and less inductively-created voltage across the wires. The laser diode is less likely to fail from voltage breakdown. Through mutual field line cancellations, less switching noise is expected and an increase level of noise immunity achieved. A more stable laser output intensity can be expected. The level of success depends on the degree to which the four principles are applied. Refer to the experiment included below for a specific comparison and quantitative results.

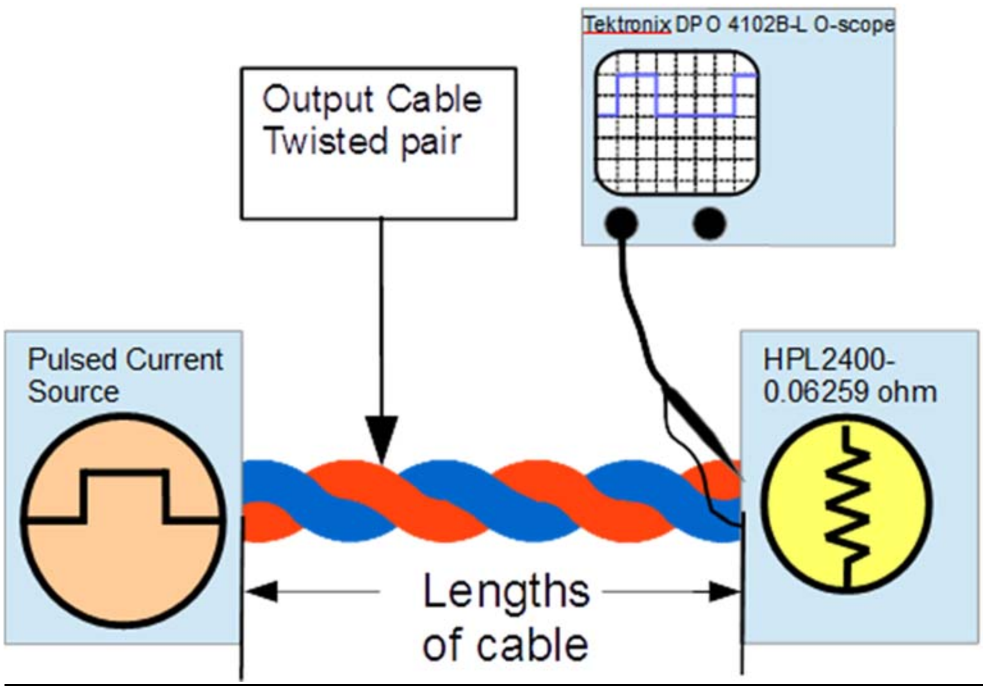
Twisted Pair Cable Experiment

The purpose of this experiment is to compare the performance of twisted pair cable to a large loop, non-twisted pair cable configuration. An oscilloscope waveform of the load voltage will be measured and recorded in table 2 below. More specifically, the percentage of overshoot and undershoot on the rising and the falling edges will be measured, compared and recorded in table 1 below. In addition, three different lengths of cable will be evaluated to determine practical wire length limitations. The cable lengths to be compared will be 12 inches, 24 inches and 36 inches. All the twisted pair cables will have 7 twists per inch.

Test equipment list:

Quantity	Description
1	DEI Current Pulse Source PIM 50
2	DEI Load HPL2400—0.06259 ohm/2400 W
1	Tektronix DPO4102B-L oscilloscope
1	DEI 37 pin adapter board (5045-0070 Rev B female)
6	22 gauge 19/34 Type E red and blue hook-up wire various lengths. (All twisted pair cables have 7 twists per inch.)

Basic Test circuit



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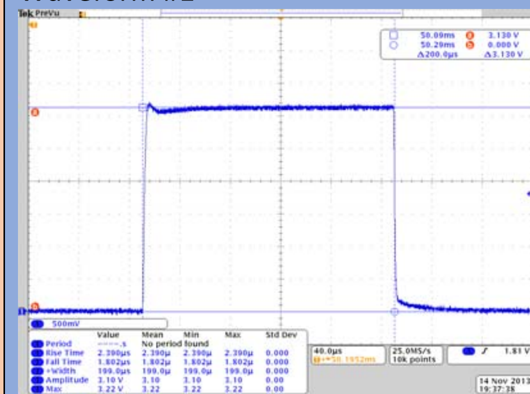
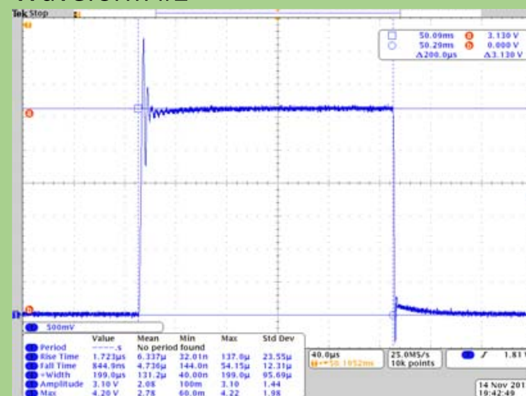
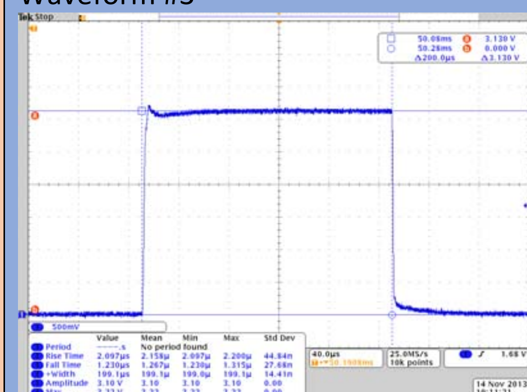
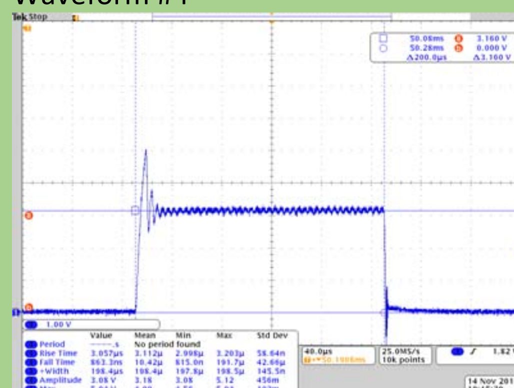
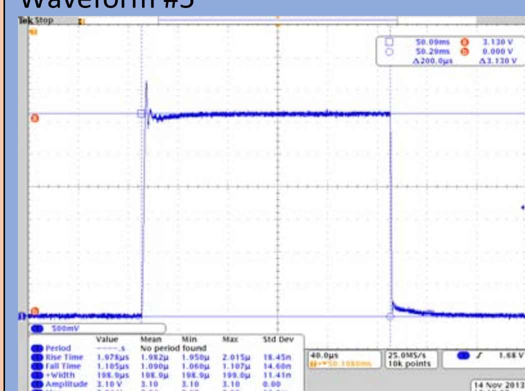
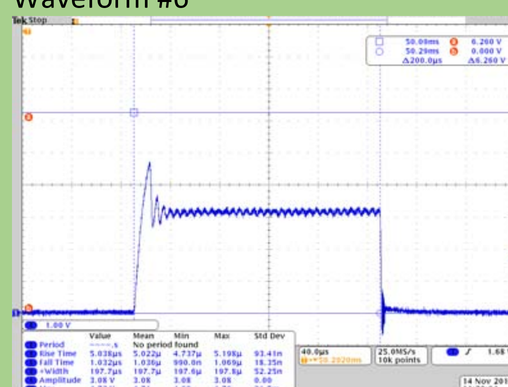
Test Circuit Operating Conditions:

1. Current pulse amplitude is 50 A
2. Rise and fall times are greater than 100 ns
3. Pulse width is 200 us
4. Frequency is 20 Hz
5. Load is 62.59 mΩ
6. Wire type is 22 gauge Type E 19/34
7. Twisted pair is 7 twists per inch

Table 1 Test Results

Cable Length	Twisted Pair Cable			Untwisted Cable		
	Over shoot	Under shoot	Waveform number	Over shoot	Under shoot	Waveform number
12 inches	3.19%	0%	#1	36.50%	12.78%	#2
24 inches	3.19%	0%	#3	58.50%	31.64%	#4
36 inches	15.97%	0%	#5	51.11%	22.36%	#6

Table 2 Test Waveform Results

Cable Length	Twisted pair cable	Untwisted pair cable
12 inches	Waveform #1 	Waveform #2 
24 inches	Waveform #3 	Waveform #4 
36 inches	Waveform #5 	Waveform #6 

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Important Note! In Waveforms #4 and #6 above, the overshoot was so excessive that the scale was changed 2X just to capture it all.

Conclusion of experiment

All three lengths of untwisted cable performed badly. The least overshoot was 36.5% and the most was 58.5%. In most cases, this much excessive voltage will disrupt the laser diode performance and very likely damage the laser diode. The least undershoot for the non-twisted cables was 12.78% and the most was 31.64%. Undershoot of this magnitude could forward bias the laser diode during what should be the off portion of the pulse. This could be very detrimental to the laser performance.

On the other hand, there was no undershoot observed for all three lengths of twisted pair cable. No difference in performance between the 12-inch and 24-inch twisted pair cables was observed. Both lengths of twisted cable had a 3.19% overshoot and 0% undershoot. Although not included in this test, under the same test conditions I would expect a twisted pair cable 6 inches or less to result in an overshoot of 1% or less. The overshoot for the 36 inch twisted pair cable was 15.97%. This author's opinion is that 15.97% is too much overshoot and is therefore not an acceptable solution. Basically the test results indicate that using a 12-inch or 24-inch twisted pair cable would be acceptable. Certainly a cable of 6 inches or less would be expected to perform even better. If a cable longer than 36 inches is required, an alternative output cable method should be chosen such as flat copper strip line or a special coaxial cable.

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