An Examination of the Amateur Scientist Circuitboard Nitrogen Laser

Contents:

Abstract

Many Do-It-Yourselfers have built nitrogen lasers, often from a design published in the Amateur Scientist column of Scientific American magazine. This page discusses the text of that column in some detail, and shows several ways in which the explanation of the design and how it operates is faulty.

To Begin

In the *Amateur Scientist* column, on page 122 of the June, 1974 issue of Scientific American, there was a design for a tabletop nitrogen laser. It was written by someone named Jim Small, who was a student at MIT at the time. The article was later republished in the Scientific American book *Light and Its Uses*, and is also on the CD of *Amateur Scientist* columns, which you can get from The Society for Amateur Scientists. I have also found this CD available from The Surplus Shed, and from American Science and Surplus.

The design isn't bad at all: it's easy to build, easy to operate, and puts out enough energy to drive a small dye laser. In fact, people are still building lasers from it today. Unfortunately, there are serious problems with the author's explanation of how it works.

I'm not about to violate copyright by reproducing the drawings from the article, and I don't have time to redraw them, so it will help you to have a copy in front of you. If you don't already own *Light and Its Uses* or the collected Amateur Scientist columns on CD-ROM, you can probably find the book or the magazine at your local public library or the nearest college or university library of Physics, Engineering, or Sciences. Alternatively, if it is still up on the Web, this page has copies of the illustrations on it. They aren't very large, but you should be able to see enough to follow what I have to say.

Mr. Small's explanation of the general principles of operation of the nitrogen laser appears, for the most part, to be reasonable. For example, he identifies one cause of the short pulses as bottlenecking in the lower laser level: the lifetime of the upper laser level is on the order of 40 nsec at low pressures, and is perhaps 20 or 30 nsec at the pressures ordinarily used in low-pressure nitrogen lasers; the lifetime of the *lower* level, on the other hand, is some tens of µsec, literally about a thousand times as long. Broadly speaking, this limits the pulsewidth to less than the lifetime of the upper level.

That is certainly correct as far as it goes; but in practice, the pulses from many nitrogen lasers (including the Scientific American laser) are considerably shorter, often in the 6 to 8 nanosecond range. This is because most small-scale driver circuits "run out of steam" — within a few nanoseconds after lasing starts, they cease to be able to give the electrons in the discharge enough energy to pump nitrogen molecules to the upper laser level at a sufficiently rapid rate, and the existing inversion is then depopulated by the lasing process. Lasing ceases long before there is time for a large lower-level population to build up. [This is supported by the fact that various high-power nitrogen lasers put out pulses that are more than 15 nsec long.]

It is, of course, possible to get a very short pulse from a nitrogen laser by pumping (and presumably lasing) about half of the available nitrogen molecules. At that point you have bottlenecking in the lower level regardless of the duration of the output pulse. At any reasonable pressure, however, doing this in just a few nsec takes far more electrical input than the Scientific American laser could possibly provide, and I have seen only one or two reports of high-power nitrogen lasers that appear to operate in this regime.

It is also possible, though not particularly common, to create a resonant shortening of the laser pulse; this also has to do with the design of the driver circuit, but in a different way. See the Tsui, Silva, Couceiro, Tavares Jr, and Massone reference, below, for more information.

Please note: some references claim that the short lifetime of the *upper* laser level limits the pulsewidth. That's idiotic nonsense. Lots of organic laser dyes that have upper-level lifetimes of just a few nanoseconds will happily run for 1 microsecond or longer under flashlamp pumping, and can even be operated CW with laser pumping.

Let's take a look at some of the claims in the article, see what they mean, and find out how they stack up against observable reality.

1. The Renowned Blumlein Circuit

First of all, Small describes his laser as a Blumlein circuit, and speaks of "the Blumlein phenomenon".

The *real* Blumlein phenomenon is the fact that **Alan Dower Blumlein** essentially invented stereophonic sound. He even got a patent on it. Among audio engineers, he is rightly famous. There are Web pages about this, and someone has written a biography of him. Among electrical engineers, however, he is also known for his work on transmission lines. He came up with something called a "Blumlein line" or "Blumlein circuit", or sometimes just "Blumlein".

This circuit involves two *matched* transmission lines, with a *matched* load between them that has twice the impedance of either line. There's an explanation of it among the pages of Kentech Instruments. (Look down the left edge of the page for the heading that says "All Documents"; choose that, and search for "Blumlein".)

Note that the two transmission lines do not have to be of the same length; but they do have to have the same characteristic impedance, and the load must be matched to both of them. This implies that the load must also have a specific impedance, which does not change. (The Kentech page includes diagrams showing idealizations of what happens when the impedance of the load is or is not matched to the impedances of the transmission lines.)

It is important to note that this is a *transmission line* circuit we're talking about here, and that, as such, it involves relatively well-behaved and well-matched impedances. The impedance of a nitrogen laser's discharge channel changes constantly during the discharge cycle, and is nontrivial even to define. It is not really possible to match such an impedance with a transmission line, which has fixed parameters. Various articles (see, for example the Tsui *et al.* and Persephonis references, below) have discussed this or related issues.

The Blumlein circuit also requires extremely fast switching, because otherwise the energy storage devices behave as discrete capacitors, not as transmission lines. This is crucial, and is a major point of failure of Small's explanation. (More about this shortly.)

If you read the references I list at the end of this rant, you will find repeated statements to the effect that the measured risetimes of these lasers are much too long for any transmission-line behavior to occur, at least on the switched side. (There is, however, some chance of observing transmission-line behavior on the *unswitched* side in a well-designed laser of this type.) Note that I'm not talking about theory here — these are actual measured risetimes of real lasers, most of them a lot better than Small's. Some of them, in fact, put out several megawatts of power, whereas Small's design puts out perhaps 50 or 100 kilowatts. (I will provide a relevant diagram later.)

1A. Switch Closure Timing, a Central Issue

In his article, Small states that "at the instant the switch closes", a discharge wave is initiated in the circuitboard capacitor that presumably forms one of the transmission lines of the device. Let's think about that for a moment.

First off, the word "instant" is not defined in physics, electronics, or engineering, except when people are discussing mathematical entities ("...the instantaneous value of the second derivative..."). It's not appropriate here, and in plain point of fact, it's meaningless. (That should serve as a pertinent warning about *any* description of a physical device that employs this word.)

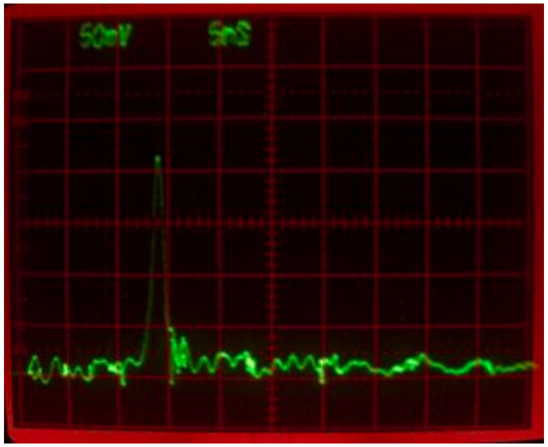
Second, even if we were to pretend that "instant" had a meaning, that it meant, say, "appreciably less than 1 nanosecond," there wouldn't and couldn't be any such instant in any case. The switch in question is an untriggered spark gap, designed and constructed so that it includes a nice big one-turn inductor. Even excellent spark gaps, well designed and carefully triggered, take several nanoseconds to initiate; and the free-running spark gap in this laser is slower than even a reasonably good triggered one.

(2011.0510, afternoon and evening)

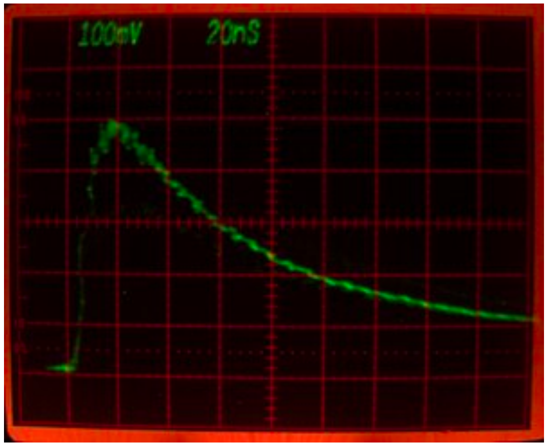
Let me show that to you.

Here are two oscilloscope traces. The first shows the output of a TEA nitrogen laser that I built. It is here to demonstrate that my scope [a Tektronix 7104, with a 7A19 vertical amplifier (600 MHz bandwidth)] and photodetector [a Motorola MRD500 photodiode (risetime specified at 1 nsec or less), in a commercial mounting] are actually fast enough to support this measurement.

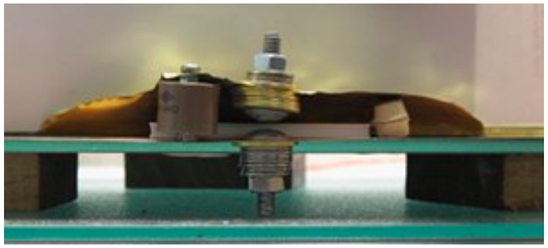
The pulse from a TEA nitrogen laser is much shorter than the pulse from the SciAm laser. If you measure it at half of its maximum amplitude, it is generally a bit less than 1 nanosecond long. It is showing up in this photo at just under 1.5 nsec, which is very reasonable — the risetime of my setup is 1 nsec or a bit more, and it is difficult to show a pulse that is shorter than the risetime of your detector/scope combination. Unless the risetime of the spark gap is still shorter, however, it will show up.



The next photo is a trace of the light from the spark gap of that same nitrogen laser. As you can see, the 0-100% risetime of the spark gap is about **18 nsec**.



Here's a photo of the gap, so you can see the design for yourself:



The top electrode is mounted on a broad piece of brass shim that comes off the top capacitor plate, so it avoids part of the inductance of the large one-turn coil that is inherent in Small's design. In addition, the gap has a starting capacitor across it [the small brown cylinder just to the left of the gap], which speeds it up even further. As a result, this gap is *at least* as fast as the one in the SciAm laser, and in fact it is probably significantly faster.

The first part of the bottom line is that I don't want to hear any idiocy about "the instant" the spark gap switches, because there isn't any such animal.

Because much of the rest of Small's explanation depends upon the switch closing in an unrealistically short time, it cannot possibly accurately reflect what is actually going on inside the laser. There are, however, other issues.

1B. Formation of a Discharge Wave

Light travels at a finite velocity, which is very roughly 300,000,000 meters per second in a vacuum or in air. In materials with higher density (and higher refractive index), it is correspondingly slower. As Small points out, a discharge wave in a transmission line travels at the speed of "light" too, but that speed turns out to be related to the impedance of the line — the electrical equivalent, if you will, of the refractive index.

In a piece of circuitboard, the speed is on the order of 5 nanoseconds per meter (see the **Schwab and Hollinger** reference). That's roughly 8 inches per nanosecond. If a discharge wave travels 8 inches during 1 nsec, then it takes 125 picoseconds to go 1 inch, and 12.5 picoseconds to go 1/10 of an inch. Please take a good look at the diagram of "The Blumlein switching phenomenon", either on the Web or in a copy of the article. In this diagram, edge of the discharge wave is shown as a vertical wall, which is totally ridiculous.

Even if we take it to represent a 10-psec risetime, there isn't any such thing as a spark gap that switches in 10 picoseconds, except perhaps in a *very* carefully designed transmission line, pressurized to about 1500 psi.

In fact, as you can see from the oscilloscope trace, above, it takes literally hundreds of times as long as that for even a good spark gap of the regular sort to turn on at these voltages and currents. If such a switch could make a discharge wave at all, the leading edge of that wave would be *several meters wide*, not the vertical wall that is shown in the diagram; and you obviously can't have a wave that is several meters across in a device that is, itself, less than half a meter wide.

As Schwab & Hollinger point out in their excellent article, for a Blumlein generator that is built from transmission lines with characteristic impedance of 0.160 Ω (a fairly reasonable value compared with the effective impedance of a laser channel that is fully conducting), it would take a spark gap with 0.2 nh series inductance to create a risetime even as short as 2 nsec. That's about the size of Small's entire laser.

10 psec? In a free-running gap that has a nice large series inductor built into it? I don't think so!

In addition, Small never addresses the fact that the laser channel can't be a well-matched load, because its characteristics are constantly changing during the electrical pulse. This makes it difficult to get any such device to operate fully in transmission-line mode, even if it is correctly designed and constructed. (If you read the references, though, you will find that it is possible to get *some* transmission-line behavior in a circuit that is sufficiently well designed, at least on the unswitched side. See the Shipman reference, in particular, for a fine example. There is also relevant information in the Fitzsimmons *et al.*; Schwab & Hollinger; and Iwasaki & Jitsuno references.)

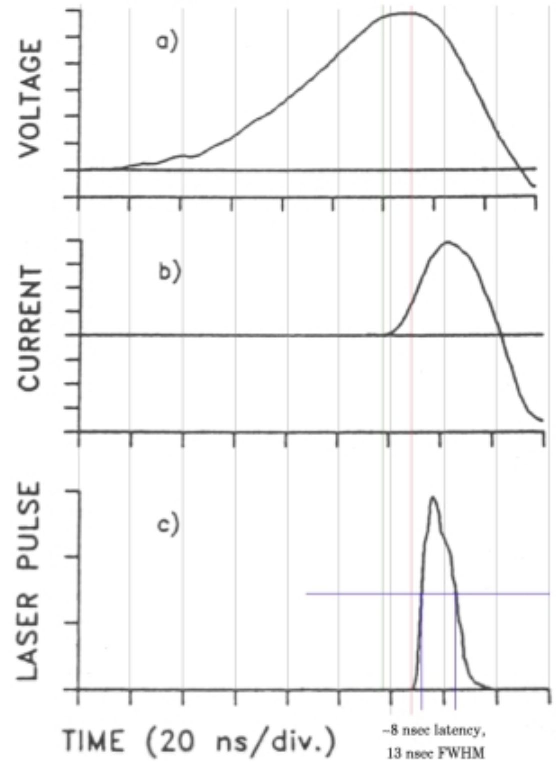
It is interesting to note that Small says, "In effect the assembly behaves as an adjacent pair of interconnected capacitors." It's not just "in effect"; his assembly *is* just a pair of interconnected capacitors; it is not a Blumlein circuit.

Unfortunately, instead of using the term "Voltage-Doubler", which would be at least vaguely appropriate even though the circuit does not actually double its voltage, he gives a distorted version of what would happen in a Blumlein device, including the claim that "As the charge rushes through the spark gap a steep difference of potential appears within the plate across a narrow boundary that separates the charged and discharged regions of the metal." Well, no. Not with the design he's describing.

(Small also indicates "no voltage" in the region of the "transmission line" where the discharge wave has passed, which would not really be correct even if the device *were* operating as a transmission line; but the issue is not particularly important to this discussion, and we don't need to get into it. If you want more and better information, read the Kentech page referred (and linked) to above, and a few of the articles cited at the end of this page.)

The Issue of Latency

Something Small never addresses (possibly because it had not yet been examined or measured when he wrote his article) is the fact that it takes time to pump enough nitrogen molecules into the upper laser level to establish a population inversion, which means that lasing does not start as soon as the spark gap begins to conduct. Here, for example, is a diagram that I have adapted from one that appears in a published paper:



(Click the small image if you want a larger one.)

First, note that this is a charge-transfer laser, so the voltage risetime is probably slower than that of a laser like Small's.

Second, note that the current in the laser channel really starts to flow about 100 nanoseconds after the voltage across the channel begins to rise. While it is true that with Small's design this time will be shorter, it is certainly going to be measured in dozens of nanoseconds.

Third, note that lasing does not begin until something like 8 nanoseconds after the channel starts to conduct; it takes time to create a population inversion. (The nitrogen laser is pumped by direct electron impact, so there can't be a significant amount of pumping going on until there is a significant amount of current flowing in the channel.)

Fourth, note that lasing ceases while there is still quite a bit of current flowing in the channel. This laser has FWHM pulsewidth of 13 nanoseconds, which puts it in the high-performance class and suggests that lower-level bottlenecking is likely to be what terminates the pulse. (The term FWHM refers to the Full Width of the pulse at Half of its Maximum value.)

3. The Travelling Wave

Another problem with Small's explanation is that he claims to have produced a travelling optical wave. Let's think about this, too, for a moment.

By Small's own admission, the output pulse from his laser is about as long as a broomstick, or a bit longer; let's say 6 feet, which is about 6 nanoseconds. If we think about a time during which the entire laser channel is above threshold, and is lasing, light that starts at either end will be amplified by the discharge in the channel, and will reach the other end just over 1 nanosecond later, because the laser channel is a little over 1 foot long.

If we assume that one end of the channel reaches threshold first, and then a hypothetical discharge wave "walks along the channel" as Small proposes, to create a travelling optical wave, what do we see from the two ends of the laser? The "back" end, where lasing starts first, should show a small amount of output, which will increase as the leading edge of the electrical discharge wave gets farther away. That is, the back end will lase first, but not very strongly, and the output from that end will increase during the first nanosecond or so until the entire channel is above threshold. (As pumping continues, the output from this end will continue to increase until either too much of the nitrogen in the channel has collected in the lower laser level, or the capacitors can no longer push enough power into the channel.)

After that first nanosecond, the discharge wave (and the initial laser light from the back end) simultaneously reach the front end, and lasing begins there. Thus, the pulse from the front end should have a much sharper leading edge than the pulse from the back end.

After that point, however, the entire channel is above threshold, so for the rest of the pulse, which is to say the next several nanoseconds, output from both ends will be identical, or nearly so. Needless to say, this fails to match Small's description of the action; but Small's description fails to match his own statements about the laser and what it does.

There are only a few ways in which such a laser, which is only 1/6 as long as the pulse it emits, can produce dramatically higher output from one end than the other, and the primary ones involve something interfering with the output at one end. In an ordinary TEA nitrogen laser, this can be a disturbed discharge that doesn't have much gain, or it can be an arc or spark. (It is, however, possible for an arc to form after lasing has ceased, so an arc by itself is not a reliable indicator.)

If anybody can show me such a laser that puts out a large pulse from only one end of its channel *without* any arc or spark formation and with no obvious visual difference between the discharge at one end of the channel and the discharge at the other, I would very much like to see it.

A travelling optical wave can be produced when a discharge wave intersects the laser channel at approximately the speed of light. This causes the excitation to "walk" down the laser channel as fast as the laser pulse does. It thus produces much more power in the forward direction than it does in the reverse direction. This phenomenon is described by Small, and it has, indeed, been observed in a discharge laser: see the John D. Shipman reference.

Of course, the discharge wave has to be relatively straight, and it has to be angled correctly with respect to the channel, so that the region of intersection advances down the channel at the speed of light. Shipman was obliged to use a series of solid dielectric switches driven by cables of precisely graduated lengths in order to create this effect, and his laser had to be rebuilt every time it was fired. It is extremely unlikely that a circular discharge wave would be effective at producing a travelling optical wave even if the Scientific American laser were capable of producing such a wave, which it clearly is not.

Alternatively, it appears to be possible to produce far more output at one end of the laser by angling the electrodes slightly so that one end of the channel is wider than the other. The usual explanation is that the narrow end of the channel begins to conduct first, which has an effect somewhat like that of a traveling discharge wave; but the length of the laser channel has to be a substantial fraction of the length of the output pulse for that effect to produce a dramatic asymmetry of power from the two ends. It seems more likely that wedging the electrodes simply produces a discharge that is better at pumping the nitrogen at one end than the other, and this is supported to some extent by visual observations of TEA lasers.

If I may once again quote Schwab & Hollinger, writing about discharge waves, **"For low-impedance Blumlein generators (as used with N_2 lasers), propagation time on the transmission lines is on the order of 5 ns/m. Considering rise times of about 25 ns, which are inherent to many reported N_2 lasers, the traveling-wave concept becomes obsolete.... If the advantages of true traveling-wave excitation shall be utilized, either multiple spark gaps, solid-dielectric spark gaps, or lines with high characteristic impedance (*e.g.,* 20 ohms) must be employed."**

The problem with high impedance is that such lines deliver only a small fraction of the current that is delivered by low-impedance lines, and must operate at much higher voltage to produce the same power levels (alternatively, you can use lots of them in parallel, as in the lasers reported in the Woodward, Ehlers, and Lineberger paper). The Schwab & Hollinger laser, btw, which does not even attempt to provide travelling-wave excitation, produces over 1 MW peak output power at 12 kV charging voltage. It's a very decent design, though not as easy to construct as some.

It is possible that Small inadvertently introduced some angle between his electrodes; but as we have already seen, that is not sufficient to produce a travelling optical wave in a laser the size of his.

To give you an example of what a *real* travelling-wave laser does, the laser described by Shipman emitted 2.5 megawatts in the forward direction and only 250 kilowatts in the reverse direction. Not surprisingly, its channel was 183 cm long, just about the length of the pulse it produced.

5. Scaling

Small claims, in his discussion of scaling, that although a discharge path one meter long can develop an output pulse of almost a million watts, "...there is a trick to it. Because the laser turns itself off so quickly, radiation does not have time to travel the full length of the column before the gain automatically drops to zero." This is just plain stupid: he himself states elsewhere in the article that the length of the pulse from a low-pressure nitrogen laser is "usually less than 10 nanoseconds"; 10 nanoseconds is more than **three** meters, so he's contradicting himself.

(As it happens, a nitrogen laser with a discharge path one meter long has developed more than three million watts, and did so without any "tricks", though Small didn't know that when he was writing his article because it hadn't been accomplished yet.)

I should perhaps point out once again the fact that the pulse can be terminated either by accumulation of nitrogen molecules in the lower laser state, or by a decrease in the electron temperature in the discharge, so that the nitrogen is no longer being pumped effectively. Most Do-It-Yourselfers are unaware of this, even though it may be what is actually happening in their lasers. It appears that at pressures on the order of 30-60 Torr, a nitrogen laser that is pumped hard enough can run for 15 nanoseconds or so, depending on its design. (For further information, see the "high power" references in the list at the end of this page.)

Second, it is true that for a very long channel, in the absence of travelling-wave excitation, the laser's output pulse would be created by only the part of the channel that the light actually succeeded in travelling through before amplification stopped. If you made the channel still longer the output would change very little, because the working length would remain the same, and any extra you added would be wasted, as its contribution would merely be absorbed at the ends after lasing ceased. If you can create actual travelling-wave excitation, of course, this ceases to be the case; but for a low-pressure nitrogen laser, the channel would have to be considerably more than two meters long before this even began to become an issue. In fact, for a few of the lasers mentioned in the papers I cite at the end of this page, specifically those with pulsewidths on the order of 20 nsec, the channel would have to be over FIVE meters long before this problem could show up.

Output Power

Small claims that the Scientific American laser puts out 50 to 100 kilowatts. I suspect that someone must have measured the output of one of these machines, but just at the moment I don't recall ever seeing any actual reported numbers. There are, fortunately, some informal ways to estimate power output. I believe that it takes only a few dozen kW to threshold a small dye laser, and the Scientific American laser can certainly do that.

There are other, somewhat informal ways to estimate peak power, but they tend to require that the laser be focused to a point, which is very difficult with most nitrogen lasers because the beam is more or less a wide ribbon shape. If you can focus down to a point, you will probably find that it takes about 200 kW peak power to produce a spark when the beam is focused onto a metal surface (be **very** careful about possible reflections!); see the Bergmann & Eberhardt reference, below. It probably takes considerably more than a megawatt to produce a spark in open air at 337 nm.

It is also possible to measure the output energy, and if you can also measure the pulsewidth it's easy to derive the power. I have a Scientech power head, which we got on eBay, and I've been able to do a rough measurement of the pulse energy of a commercial TEA nitrogen laser, also acquired on eBay. This laser, a PRA LN-1000, is rated to produce about 1.5 millijoules per pulse; I measured it at just under 1.1, which is reasonable for an older machine in less than perfect condition. It is more than powerful enough to run small dye lasers.

If you don't have a power head, you can make one from a thermoelectric cooler held to a block of aluminum with heatsink grease between them, and some flat black paint. The advantage of the Scientech head is that it has a built-in calibration heater; but it can't be too difficult to construct a homebrew head with such a heater.

In Closing

I have to confess that crap like Small's explanation drives me right up the wall, especially in the pages of Scientific American (which used to be a real science magazine), and *double*-especially when it comes out of MIT.

Anyone who bothers to perform any kind of decent testing on a laser built to Small's design can't fail to detect the huge bogosity quotient, and I can't believe that he didn't have access to decent equipment, MIT being, after all, one of the premier institutions for this sort of thing in the entire world.

Moreover, just reading the Shipman article carefully is enough to tell you that Small's laser can't do what he claims it does, and that article was published two years before Small's Scientific American piece, so presumably he had access to it. It's even moderately likely that he read it, though apparently not carefully enough. Small certainly should have known that there's no such thing as an instant in physics, and that even a one-turn coil (such as the one he builds into his spark gap) has substantial inductance.

Argh.

In Small's defense, I have to point out that there was relatively little literature available to him; almost all of the nitrogen laser articles I've got were published after the Scientific American nitrogen laser appeared. On the other hand, Shipman's article is quite clear about some of the conditions that must be achieved in order to create a travelling discharge wave. (Shipman even suggests the technique of using multiple coaxial cables that later became the basis of the Woodward, Ehlers, & Lineberger lasers; and he suggests graduated lengths to create travelling-wave excitation, which those lasers didn't use, though their article mentions the possibility.)

Residual Fallout

Unfortunately, the explanation given in the Scientific American article is an example of the worst effects of bad scholarship (and accidental memetic engineering): its claims have been believed and repeated by a great many people who failed to check or fully understand them, and they have polluted a large sector of amateur and even professional nitrogen laser work. I have seen the words “At the instant the switch closes” in articles from major journals, for example. Also, although it isn’t just Small’s doing, the term “Blumlein” has become hopelessly polluted. Too many articles and Web pages refer to voltage-doubler circuits as “Blumleins”. It is likely that Shipman’s laser could, with some justice, be described as a Blumlein circuit, and there are one or two others, very similar to his, that were reported; but those few are about it, as far as I’m aware. Nothing else comes close. Not your laser, not my laser, not anybody’s laser. Throughout much of the professional research literature, however, any simple voltage-doubling-circuit laser is referred to as a Blumlein circuit.

Some people even talk about how “easy” it is to build Blumlein circuits. See, for example, the comments about Ben Franklin in Sam’s Laser FAQ. In fact, the subject of Blumleins is about the only thing that bothers me about Sam’s otherwise remarkably excellent set of pages. (If you didn’t arrive at this page from his, you should definitely go take a look. I cannot recommend Sam’s pages too highly — they contain a huge amount of extremely valuable and useful information for the DIY laser builder and enthusiast, as well as lots of helpful links.)

It also seems to me that Small never actually performed rigorous measurements on his laser, else he wouldn’t have made such grandiose claims for it. As I said above, it’s a nice straightforward design; the only two things that are really wrong with it, aside from his ridiculous claims, are: first, the fact that epoxy-fiberglass circuitboard is very lossy at high frequencies, which makes it a mediocre candidate for this service. It’s readily available, though, and not very expensive, so that isn’t as bad as it might be. (Just for reference, btw, I think the dielectric constant of G-10 circuitboard is about 5.2 or 5.3.) Second, the spark gap could very easily have been a *lot* better.

I might also point out that Small misuses the word “superradiance”, but in fact almost everybody does that. A better term for a laser that operates without any mirrors is “superfluorescence”. (If I remember correctly, R. H. Dicke proposed the term “superradiance” to describe a specific phenomenon he envisioned, something that is fairly specialized, and is rarely observed.)

As to travelling-wave excitation (or any method for creating TW optical behavior) in an amateur low-pressure laser, if anyone cares to come forward with a convincing demonstration of this I’ll be only too happy to mention it here, and to link to it if there’s a Web page for it. (I know of a few people who are working on TW TEA nitrogen lasers, but I am not aware of anyone who is trying it at low pressure.) Do be sure, however, that you have adequate instrumentation and that you aren’t just fooling yourself.

References:

H. G. Heard
“Ultra-violet Gas Laser at Room Temperature”
Nature, v. 200 (1963), p. 667

This article presents the discovery of the nitrogen laser.

A. W. Ali
“A Study of the Nitrogen Laser Power Density and Some Design Considerations”
Applied Optics, v8n5, May 1969, pp 993-996

This is a fine article, written only a few years after the nitrogen laser was discovered.

John D. Shipman
“Traveling Wave Excitation of High Power Gas Lasers”
Applied Physics Letters, volume 10 number 1, January, 1967, pages 3 & 4.

(This is a real classic, and is central to my claims.) Shipman’s laser, as far as I can tell, actually did operate mostly in transmission-line mode, and was about as close as any to being a real Blumlein. He also makes several key points about circuitry and design.

E. L. Patterson, J. B. Gerardo, and A. W. Johnson
“Intense electron-beam excitation of the 3371 Å N_2 laser system”
Applied Physics Letters, volume 21 (September, 1972) pages 293-295.

I have not read this article, but I believe that it reports generation of 24 MW, easily the highest peak power that I have ever heard of in a believable nitrogen laser. There is a paper in *Comptes Rendus* for February, 1972 that claims 50 MW by direct electrical excitation, but I did not find it to be particularly believable.

"Réalisation d'un amplificateur laser d'une puissance atteignant 50 MW à 3 371 Å dans l'azote moléculaire."
Jean-Pierre Girardeau-Montaut, Michel Roumy, Joël Hamelin, et Louis Avan, présentée par M. Alfred Kastler
Comptes Rendus [Série B] 274(9) (28 Feb, 1972), pp. 607-610

[As of September, 2013, you can find this paper on the Web at http://visualiseur.bnf.fr/ark:/12148/bpt6k5794353k]

Adolf J. Schwab and Fritz W. Hollinger
"Compact High-Power N_2 Laser: Circuit Theory and Design"
IEEE Journal of Quantum Electronics, volume QE-12, number 10, October, 1976, pages 183-188

This makes the crucial point that for a transmission line with impedance of 0.16 ohms, you can achieve a 2-nanosecond risetime only if your switch has inductance of less than 0.2 nh, which the authors point out "is unrealizable using a single spark gap." Real voltage-doubler lasers usually have risetimes more like 25 nsec.

W. A. Fitzsimmons, L. W. Anderson, C. E. Riedhauser, and Jan M. Vrtilek
"Experimental and Theoretical Investigation of the Nitrogen Laser"
IEEE Journal of Quantum Electronics, volume QE-12, number 10, October, 1976, pages 624-633

Even though their own Figure 7 clearly shows many reflections on their "transmission line" during a single pulse, which proves that the device is operating mostly as a capacitor and not as a transmission line matched to a load, they nonetheless describe this version of their laser as a "Blumlein". That, however, is about the only problem I have with the article, which is otherwise excellent and thorough.

B. W. Woodward, V. J. Ehlers, and W. C. Lineberger
"A reliable, repetitively pulsed, high power nitrogen laser"
Review of Scientific Instruments, volume 44, 1973, pages 882-887

The lasers in this article use coaxial cables as "peaker" caps; the cables operate at least partly as transmission lines. The experimenters didn't try to create a travelling optical wave, but the design should easily lend itself to that kind of effort, and there is mention of one possible method (graduated cable lengths).

A key quotation:

"Further, the impedance of the laser gas after breakdown has started is very small, so that the maximum coupling of power to the discharge will occur when the impedance of the transmission line is minimum (in the range available)."

Seishiro Saikan and Fujio Shimizu
"Water spark gap for a nitrogen laser"
Review of Scientific Instruments, volume 46 number 12, December, 1975, pages 1700 & 1701

With a spark gap that goes *through* the circuit board rather than around it, and a spacing of 0.1 mm, these researchers measured a risetime of 1-2 nsec for their switch. They do state that the actual risetime was probably somewhat faster, because the driving circuitry itself had a risetime of about 1 nsec. On the other hand, they point out that a water-filled gap is a dielectric switch under their conditions, and they note that dielectric switches display fast switching characteristics. This is supported by the work of Shipman; see the reference to his article, above. It also shows that Small's laser cannot generate a discharge wave, most especially one with a 10-picosecond risetime!

Chigusa Iwasaki and Takahisa Jitsuno
"An Investigation of the Effects of the Discharge Parameters on the Performance of a TEA N_2 Laser"

IEEE Journal of Quantum Electronics, volume QE-18, number 3, March, 1982, pages 423-427

These guys actually tried different spark gaps, and they report the performances they got. Again, they refer to their laser as a Blumlein, which it clearly isn't; but it is sufficiently similar to Jim Small's design that it is relevant. If I may quote,

"In a laser discharge device using a transmission line as a discharge capacitor, the duration of the current pulse is affected by the reflection of the voltage pulse at the open end of the transmission line (so-called transmission line effect), and therefore, the laser output may depend on the roundtrip transit time in the transmission line when the transit time is smaller than the lifetime of the upper state.

".... However, no appreciable voltage wave arising from the reflection in the transmission line has been observed in the measured waveform of the anode voltage. This may be due to the fact that the rise time of the voltage wave (~5 ns) is much longer than the transit time, and therefore, it is supposed that the transmission line effect does not play an important role in this case...."

(Note that this is a TEA laser, where the lifetime of the upper state is perhaps 2 nsec, and they calculated the roundtrip transit time of their capacitor to be 1.3 nsec.)

The key thing here is the risetime of the voltage in their "Blumlein", which was 5 nsec. This is vastly longer than the risetime that would be required to create a voltage wave in a device the size of Small's, and is also vastly longer than the risetime he indicates in his diagrams and text. It is, moreover, a *measured* risetime, in a real device, and not just handwaving.

J. I. Levatter and S. C. Lin
"High-power generation from a parallel-plates-driven pulsed nitrogen laser"
Applied Physics Letters, volume 26, pages 118-120, 1975

The authors of this (excellent) article built a truly righteous laser; it developed three megawatts of output power, and was for some time the most powerful purely discharge-pumped nitrogen laser on record... but even though they tried to design it to create a travelling optical wave, they were unable to find any evidence of one.

Riccardo Polloni
"Design of a reliable, high-power, nitrogen laser"
Optics and Quantum Electronics 8(6) (1976), p. 565-566

[This paper is cited by the Oliveira dos Santos *et al.* paper, and is included here for completeness. I haven't read it yet.]

B. Oliveira dos Santos, C. E. Fellows, J. B. de Oliveira e Souza, and C. A. Massone
"A 3% Efficiency Nitrogen Laser"
Applied Physics B (Photophysics and Laser Chemistry) 41 (1986), pp. 241-244

This is a strange and intriguing article that illustrates an entirely different approach. Using a coaxial capacitor of only 800 pf, driven by one of three "dumper" caps (1.5, 10, or 20 nf), they achieved up to 3 MW output power at efficiencies ranging as high as 3%. Peculiarly, their pulsewidth decreased as the amount of stored energy increased, which may suggest that they are pumping a substantial fraction of the nitrogen molecules in their laser. Well worth reading and thinking over very carefully.

Unfortunately, an attempt by Dr. Vicente Aboites and colleagues to reproduce the performance of this design did not succeed:

V.J. Pinto, V. Aboites and J. de la Rosa,
"High Efficient N2 Laser"
Revista Mexicana de Fisica, 37(3) (1991), pp. 391-395

(See below for other articles by Dr. Aboites.)

K. H. Tsui, A. V. V. Silva, I. B. Couceiro, A. D. Tavares, Jr., and C. A. Massone
Resonant Narrowing of the Nitrogen Laser Pulse by Plasma Impedance Matching

IEEE Journal of Quantum Electronics, Vol. 27 No. 3 (March, 1991), pages 448-453

This article, though not necessarily easy to follow, contains a valuable discussion of a topic that is seldom discussed in the nitrogen laser literature. It may explain (at least partly) the occasional high-performance laser operating at relatively low pressure but producing extremely short pulses, for example the Armandillo and Kearsley laser (see below).

A. D. Papadopoulos and A. A. Serafetinides
"Characteristics of Doubling Circuits Used in Gas Laser Excitation: Application to the N_2 Laser"
IEEE Journal of Quantum Electronics, volume 26 number 1, January 1990, pages 177 to 188

Note that this laser closely resembles the Scientific American laser, but is much faster and produces considerably higher output. Nonetheless, the authors describe it as a doubling circuit, not as a Blumlein; and they analyze it in terms of lumped constants, not transmission lines. The oscilloscope traces of the current and voltage waveforms in their laser and of the laser output pulse support this approach.

P. Persephonis
"Electrical behavior of a Blumlein-line N_2 laser"
Journal of Applied Physics, volume 62, pages 2651-2656, 1987

This early Persephonis article is good, despite the misuse of the term "Blumlein", but see the next reference.

P. Persephonis, B. Giannetas, J. Parthenios, C. Georgiades, and A. Ioannou
"Capacitance Allocation and Its Role in the Performance of Doubling-Circuit Pulsed Gas Lasers: Its Application to the N_2 Laser"
IEEE Journal of Quantum Electronics Vol. 29, No. 8, August, 1993, pages 2371-2378

This is a beautiful look at the optimum capacitances and capacitance ratio for the doubler circuit nitrogen laser. (Note that by 1993, Persephonis had ceased to refer to these as "Blumlein-lines".) The findings in this article are somewhat surprising, in that they obtain best results with relatively large capacitances; but entirely expectable in that they confirm the general wisdom, which is that the capacitors in a doubling circuit should be of about equal value. To say that this article is well worth reading would be an understatement.

Imre Sánta, László Kozma, Béla Német, János Hebling, and M. R. Gorbal
"Experimental and Theoretical Investigation of a Traveling Wave Excited TEA Nitrogen Laser"
IEEE Journal of Quantum Electronics, vol. QE-22, Number 11, (November, 1986), pages 2174-2180

These people figured out how to angle the electrodes in order to cause the discharge to form at one end and walk down the cavity to the other. Because a TEA nitrogen laser has an output pulse that is only about 600 psec long, it is possible to make a TW laser that is only about a foot long, and they appear to have done so. DiY folks take note.

K. R. Rickwood and A. A. Serafetinides
"Semiconductor Preionized Nitrogen Laser"
Rev. Sci. Instr. 57(7), July 1986, pp 1299-1302

A rather intriguing paper for its general premise; also has some good information about optical cavity considerations, and about the effects of adding helium to the gas. Well worth a careful read.

E. Armandillo and A. J. Kearsley
"High-power nitrogen laser"
Applied Physics Letters, volume 41 number 7, (1 October, 1982), pages 611 through 613

This article covers the design considerations of a nitrogen laser that delivered 5 MW (!), the highest output power reported in a discharge-pumped nitrogen laser up to the time of the article's publication, and probably still one of the highest power levels ever achieved in N_2. Oddly, their pulses were only 4 nsec long, which is quite unusual for high-performance nitrogen lasers. The article is good, if a bit brief.

Crucial points here include the dimensions of their channel, which used electrodes a full 4 cm across, spaced 25 mm apart; and the fact that the addition of Helium, while it did not increase the output energy or power of their laser, did give them better pulse-to-pulse uniformity and a cleaner discharge. In addition, they were able to operate their laser with enough He to bring the total pressure up to more than 1 atmosphere. I have taken advantage of that in at least one of my own lasers: it allows you to operate without a vacuum pump, which can be very convenient.

F. Encinas Sanz and J. M. Guerra Perez
"A High Power High Energy Pure N_2 Laser in the First and Second Positive Systems"
Applied Physics B, volume 52 (1991), pages 42 through 45

This article concerns a charge-transfer ("dumper-peaker") laser that developed 20.5 mJ in the UV (!). Because it had a relatively long output pulse, however, the peak power was only 1.5 MW. One interesting thing about this article is the fact that they found an optimum interelectrode spacing of about 38 mm, much wider than is common in circuitboard (or other) low-pressure nitrogen lasers, but similar to the spacing in the high-energy laser built by Rebhan *et al.*, which is cited below.

Another key point is that the article shows voltage, current, and laser output traces taken from oscilloscope photos. These clearly demonstrate the fact that their laser didn't reach threshold until about 10 nsec after current began to flow in the laser channel, and also the fact that current didn't begin to flow until dozens of nsec after voltage began to appear across the channel. Granted, their design was a charge-transfer circuit, not a doubler circuit, so the voltage risetime was slower than you would expect in a Small-type laser; still, there is definitely some nsec delay between the onset of the discharge and the onset of lasing.

U. Rebhan, J. Hildebrandt, and G. Skopp
"A High Power N_2 Laser of Long Pulse Duration"
Appl. Phys. 23, 341-344 (1980)

This is another of the best nitrogen lasers ever constructed. With some SF6 in the gas mix, it delivered 30 mJ over 19 nsec, and even without any SF6 it delivered 16 mJ over 14 nsec! It uses a liquid-dielectric peaker cap of very ingenious design. It describes the use of long electrodes to avoid sparking at the ends, an important technique.

Godard, Bruno
"A Simple High-Power Large Efficiency N_2 Ultraviolet Laser"
IEEE J-QE vol QE-10 no 2, February 1974, pp. 147-153

This is very likely Godard's fairly infamous article in which he claims to have derived 9 MW (!) from a laser built out of kapton circuitboard. Inasmuch as nobody has ever been able to repeat the result, there is considerable skepticism. I'm not 100% sure about the reference, btw; my copy of the article was handed to me by Godard himself in either 1973 or 1974, and is not from J-QE. It says on it...

"LABORATOIRES DE MARCOUSSIS
CENTRE DE RECHERCHES DE LA
COMPAGNIE GENERALE D'ELECTRICITE
DEPARTEMENT RECHERCHES PHYSIQUES DE BASE
Section Sources d'Ondes Cohérentes
91460 - MARCOUSSIS - FRANCE"

...and is dated "MAI 1973". The title is also slightly different; it begins "A VERY SIMPLE HIGH POWER...."

Ernest E. Bergmann and N. Eberhardt
A Short High-Power TE Nitrogen Laser

IEEE Journal of Quantum Electronics vol. 9 no 8, August, 1973, pages 853-854

Bergmann (not to be confused with H. M. von Bergmann, a South African researcher who did pioneering work with TEA nitrogen lasers) and Eberhardt note that their laser's unfocused beam could pump several dyes to superfluorescence, and that sparks could be produce by focusing the beam on various metal surfaces. This laser had 200 kW peak output power, so these results provide a rough diagnostic.

A. Vasquez Martinez and V. Aboites
“High-Efficiency Low-Pressure Blumlein Nitrogen Laser”
IEEE J-QE vol QE-29 no 8, August, 1993, pp. 2364-2370

This is another important paper, though the theoretical investigation is not as thorough as in some others, and also despite the fact that the authors speak of “the instant the spark gap triggers”, which is not accurate. Even so, there is some very interesting information here. As mentioned above, Dr. Aboites has also published other nitrogen laser articles, including a MOPA or MOPO design:

Jorge Sandoval Ch, Alejandro Apolinar, Victor J. Pinto, Vicente Aboites
"Perfiles transversales de un sistema MOPO de N2"
Revista Mexicana de Fisica 43(3) (1997), p. 381

C. H. Brito Cruz, V. Loureiro, A. D. Tavares, and A. Scalabrin
“Characteristics of a Wire Preionized Nitrogen Laser with Helium as Buffer Gas”
Appl. Phys. B 35 (1984) pp. 131-133

This is a small laser, used to investigate both preionization and helium; mixing nitrogen and helium 50-50 doubled their output power. With preionization, they measured best output at E/p of 87.

Peter Schenck and Harold Metcalf
“Low Cost Nitrogen Laser for Dye Laser Pumping”
Applied Optics, Vol. 12 # 2, February, 1973, starting on page 183

Bert Pool used to have a copy of this fine article on his Web page, but I don’t find it now. It is a nice easy design that develops more than 100 kW peak power under optimum conditions. I believe that it uses a thyratron as a switch, but you could very easily build it with a spark gap instead. I will, however, advise you to use a *triggered* spark gap — they’re a lot faster than free-running spark gaps, and speed is the reason why you would want to use a spark gap rather than a thyratron in the first place.

If you want to build a nitrogen laser that puts out considerably more power than Small’s, I have published a design that delivers approximately 250 kW and is capable of making sparks when the beam is focused onto a metal surface. I am currently (late 2006) working on a laser that will be less expensive to build and should put out at least 500 kW.

Finally, I need to point everyone at a remarkable site put together by Thomas Rapp, in Germany. He really knows how to build lasers, including TEA nitrogen lasers. (You can have The Babelfish translate his pages; it does a fair job, considering, and although you’ll still have a lot of figuring out and thinking to do, it’s definitely worth doing.)

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