Pizzicato *Pulse Generator*

Your oscilloscope and the Pizzicato *create a time domain reflectometer, a handy piece of test equipment for checking your transmission line's characteristics.*

By Gary Steinbaugh, PE, AF8L

An Amateur Radio station has much in common with a violin: the transmitter is like a bow, the transmission line is like the strings and the antenna is like the wooden body. Now, a violinist will recognize the musical term *pizzicato* as a direction to pluck the strings instead of using a bow. The pulse generator described in this article electrically "plucks" a transmission line; by observing the line's reaction on an oscilloscope, you can check the line's length, terminations, and possible defects.

The radio/violin similarity is actually mathematical, as both obey the wave equation,

$$\nabla^2 \times \Psi = \frac{1}{c^2}\frac{\partial^2 \Psi}{\partial t^2}$$

The Scottish scientist James Clerk Maxwell (1831-1879) collected, completed and combined the electromagnetic equations of Gauss, Ampère and Faraday, obtaining a wave equation for the electric field, and a corresponding wave equation for the magnetic field. Maxwell showed that the wave equation's constant $1 / c^2$ (the product of the permeability and permittivity of free space) is equal to the reciprocal of the square of the speed of light in a vacuum ($c = 299{,}792{,}458$ m/s). He correctly theorized that light is electromagnetic, and paved the way for the likes of Hertz, Marconi, and Einstein. The Nobel Prize-winning physicist Richard Feynman said, "From a long view of the history of mankind — seen from, say, 10,000 years from now — there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics."[1]

You can think of a transmission line or a violin string as a row of little masses connected by springs (a *lumped-parameter* model). Any given mass is affected only by the two adjacent masses connected to it by springs. Look at the left column of Figure 1, which shows a wave being "launched" by giving the left end a tug upward, then an equal tug downward. You can see how the masses and springs yank each other up and down to form a wave that travels toward the right end (note that the

9534 Appomattox Ct
Loveland, OH 45140-7140
gsteinbaugh@yahoo.com

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[1] Notes appear on page 8.

masses do not move sideways).

What happens when the wave reaches the right end depends on whether the end is fixed, free to move up and down, etc. The middle column of Figure 1 shows the fixed case; notice how the pulse becomes inverted (changes phase) during its reflection. You can try this yourself with a rope tied to a doorknob. The right column of Figure 1 shows the free case, where the pulse is reflected without a phase change. To verify this, add a length of light fishing line between the rope and the doorknob. If the right end is connected to a shock absorber with the right damping (matching impedance), the pulse will be completely absorbed; we aspire to this case for our antennas.

Speed and VF

By measuring the time it takes for the wave to return and by knowing its speed, we can calculate the length of

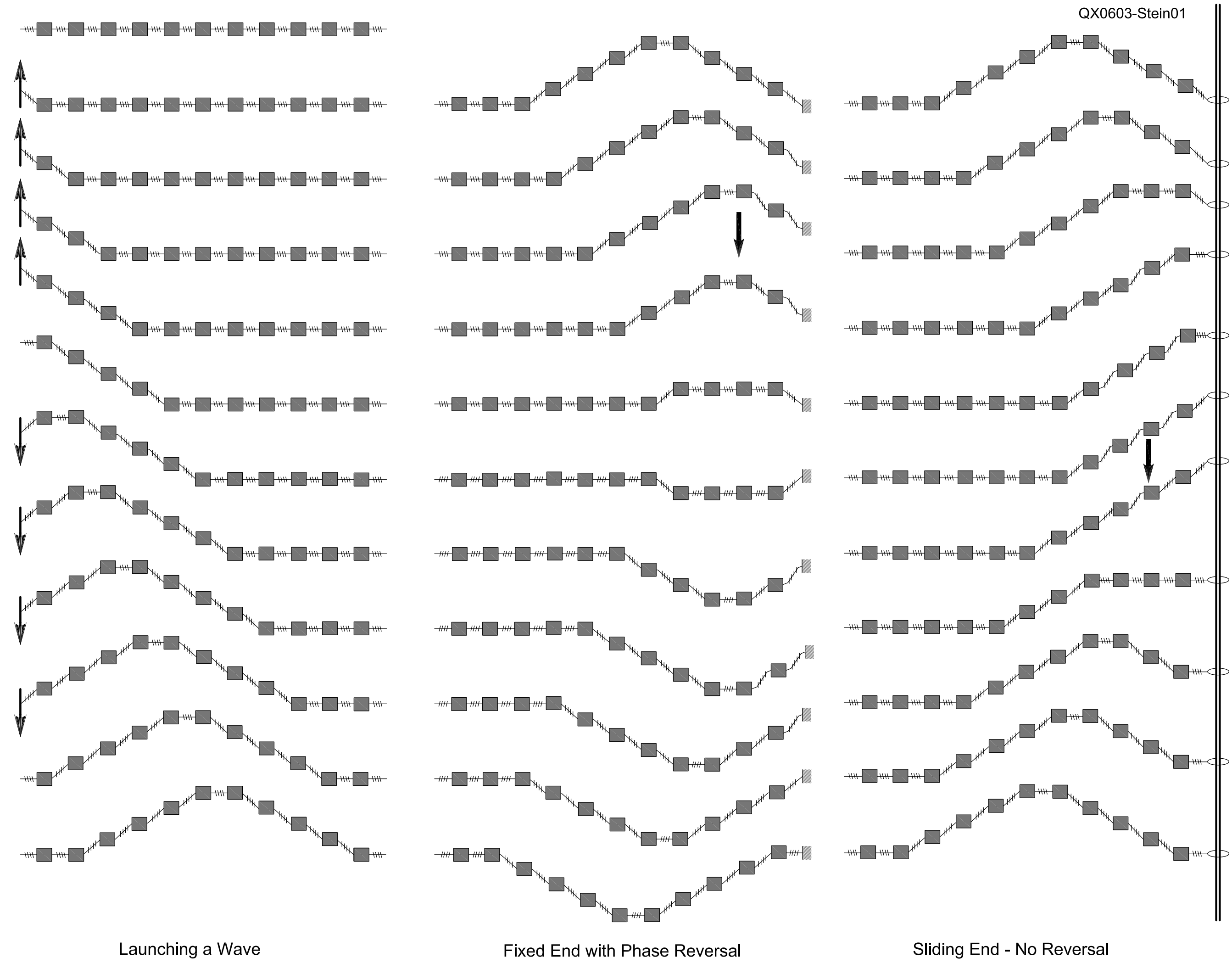


Figure 1 — Wave in a lumped-parameter model.

Table 1
Velocity Factor Tabulation: Theoretical

Transmission Line	*meters / sec*	*feet / sec*	*Velocity Factor*	*Round Trip meters / ns*	*Round Trip feet / ns*
Space (vacuum)	299792458	983571058	1.00	0.149896229	0.491785529
Air, 600 Ω open wire	293796609	963899637	0.98	0.146898304	0.481949814
450 Ω twinlead	263817363	865542531	0.88	0.131908682	0.432771266
300 Ω twinlead	245829816	806528268	0.82	0.122914908	0.403264134
Coax (foam)[2]	239833966	786856846	0.80	0.119916983	0.393428423
Coax (polyethylene)[1]	197863022	649156898	0.66	0.098931511	0.324578449

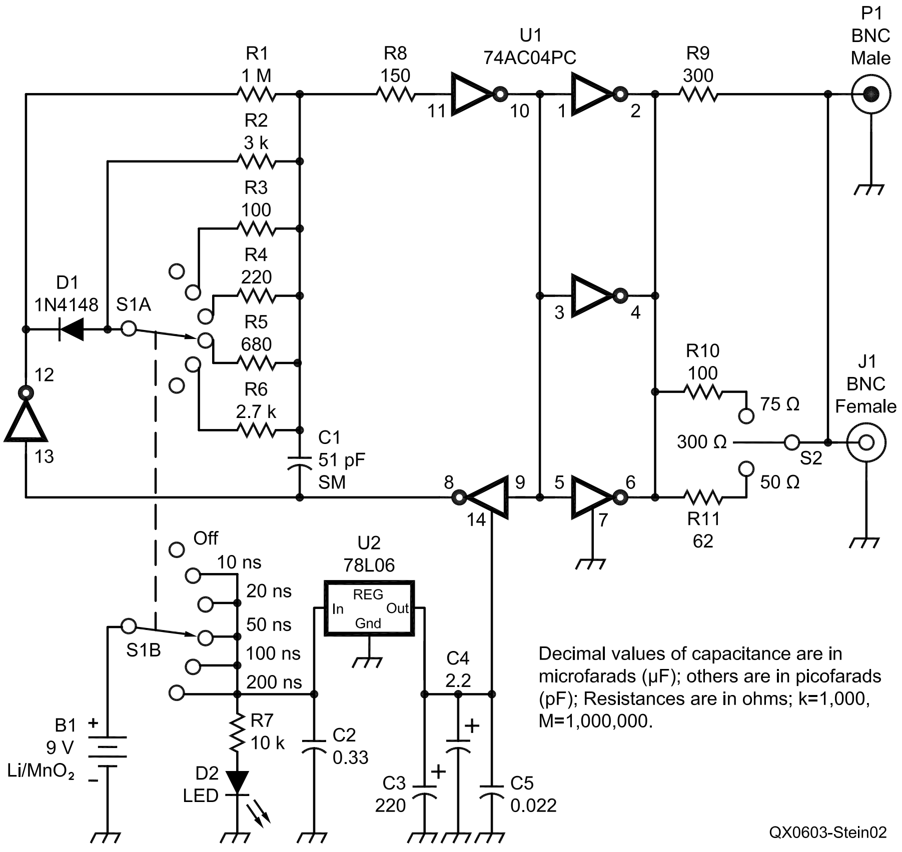
[1] RG-8, RG-11, RG-58, RG-59, RG-174, etc.
[2] Foam versions of above, and hardline.

the line. Electromagnetic waves travel slower in any material than in a vacuum (if they didn't, lenses wouldn't work), and this actual speed divided by c is called the *velocity factor*. Tables 1 and 2 show these speeds in common transmission media and their corresponding velocity factors; also shown is the out-and-back travel time, so distance may be calculated simply by multiplying the time between pulses by the appropriate speed. These numbers are too precise for real-world work, so practical values are also included. Some cable manufacturers publish measured velocity factors for their cables, and using their numbers would increase the accuracy of your results.

Resolution will be limited by the rise time of both the oscilloscope and the pulse generator. I began experimenting with a CMOS 555, but with a minimum pulse width of 100 ns and a rise time of about 15 ns, it was apparent that it would be too slow. I stumbled upon a pulse generator article in *Electronic Design*[2] that used Advanced CMOS, which is more suited to this application, having a rise time of 3.5 ns (yielding a resolution of about 1½ feet) and an output source/sink capability of 24 mA. Among other modifications to that design, I used a 74AC04 hex inverter in a three-gate ring oscillator circuit, with the remaining three gates as buffers. Figure 2 is the schematic diagram for the *Pizzicato*, essentially a square wave oscillator with a very low duty cycle. C1 charges through R1, but discharges through D1 and the parallel combination of R1 and R2 (and R3, R4, R5 or R6, depending on the setting of S1, a six-position miniature rotary switch that also serves as the power switch). This produces pulse widths useful for the line lengths that Amateur Radio operators are likely to encounter; the oscillator waveforms are shown in Figure 3. R8 is included to keep the 9 V and –3 V spikes from producing a gate input current that exceeds the limit of 20 mA. S2, an ON-OFF-ON toggle switch, provides the proper impedance for 50 Ω, 75 Ω and 300 Ω lines; obviously R9, R10 and R11 could be recalculated for other impedances. Although I have only used the *Pizzicato* for radio applications, it should be useful for any transmission line, eg, LAN cables and telephone wires.

LiMnO$_2$ for Longer Life

My circuits often seem to design themselves. I had planned on using a common 9 V alkaline battery, but the AC logic series has an absolute maxi-



Decimal values of capacitance are in microfarads (µF); others are in picofarads (pF); Resistances are in ohms; k=1,000, M=1,000,000.

Figure 2 — Schematic diagram of the Pizzicato Pulse Generator.

BT1 — 9 V lithium/manganese dioxide battery, NEDA 1604C.
P1 — BNC male panel mount, Alltronics CB111.
S1 — 0.5 inch rotary switch, 2 pole, 6 position, Mouser 633-MRK206A.
S2 — 0.5 inch toggle switch SPDT on-off-on.

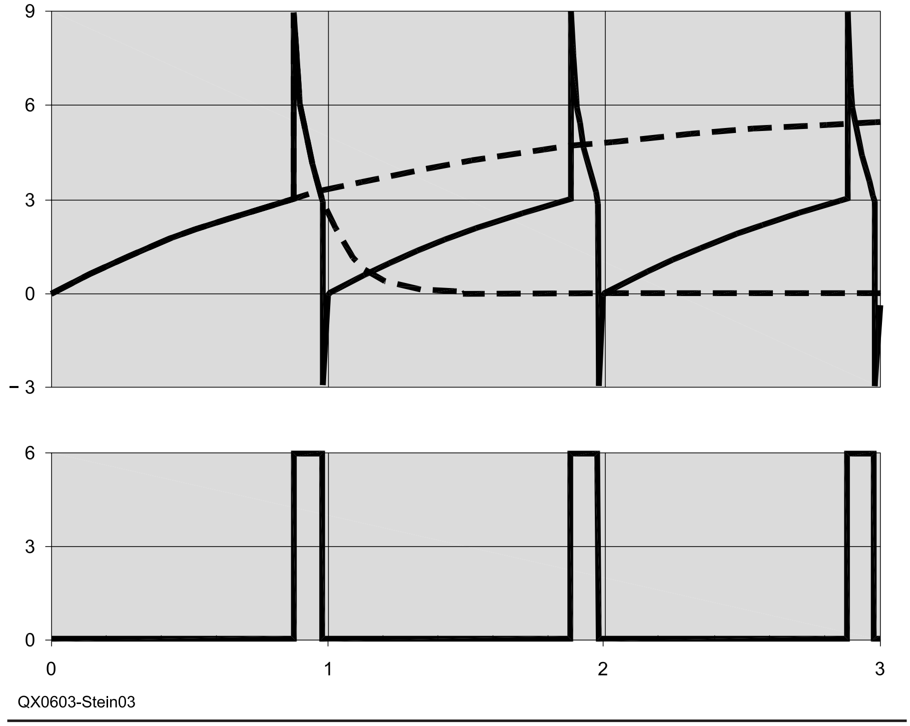


Figure 3 — Oscillator waveforms.

mum V_{cc} of 7 V, so I added a 78L06 6 V regulator, with a 2 V dropout. This meant that the battery terminal voltage had to be a minimum of 8 V, but ordinary 9 V batteries discharge quickly to 7 V. This led me to lithium/manganese dioxide batteries, which have higher initial voltages and much longer lives. Figure 4 shows discharge curves for carbon/zinc, alkaline, and $LiMnO_2$ batteries. The battery is restrained by the box lid, and by the two switches, which are both 0.5 inch wide.

I built the circuit on a small scrap of perforated protoboard, trying to keep the leads as short as possible; Figure 5 shows the top of the board, while Figure 6 shows the bottom. The enclosure is a RadioShack 270-1801 ABS box, 3 × 2 × 1 inches with molded-in card slots. I had to do a little plastic surgery with a Dremel tool to remove some interfering bosses, and since the bottom would become the front, I sanded off the feet. Figure 7 is an inside view of the pulse generator. Ordinarily, I would not suggest such compact construction, but the high frequencies involved begged for an exception.

I had a RadioShack 276-068 red LED in a chrome holder, but I was appalled at the dim light level, even at 20 mA (the entire rest of the circuit draws 6 mA). Intending to substitute a brighter LED, I carefully removed the original, only to find that it was 4 mm in diameter instead of the standard 3 mm or 5 mm. Not to be thwarted, I bought a 276-320 white 5 mm LED, chucked it in my hand drill, and carefully sanded it down to 4 mm with an old emery board that my wife had discarded. I soldered a 10 kΩ resistor to the positive lead and glued the assembly in the empty holder. The result is a brilliant pilot light that draws only 500 µA.

Figure 8 is the front of the *Pizzicato*. I made the decal by printing the colored artwork on Micro-Mark Decal Paper (item 82272, from **www.micromark.com**), spraying it with Krylon Crystal Clear Acrylic Coating (1303A), and applying it like a common decal.

Figure 9 displays the oscilloscope screen with the *Pizzicato* "plucking" one end of a length of foam-insulated RG-8U with a 10 ns pulse; look closely

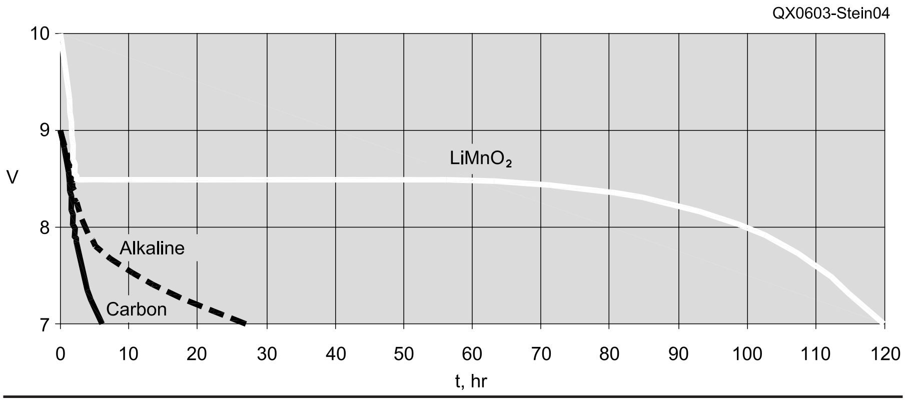


Figure 4 — Battery discharge curves.

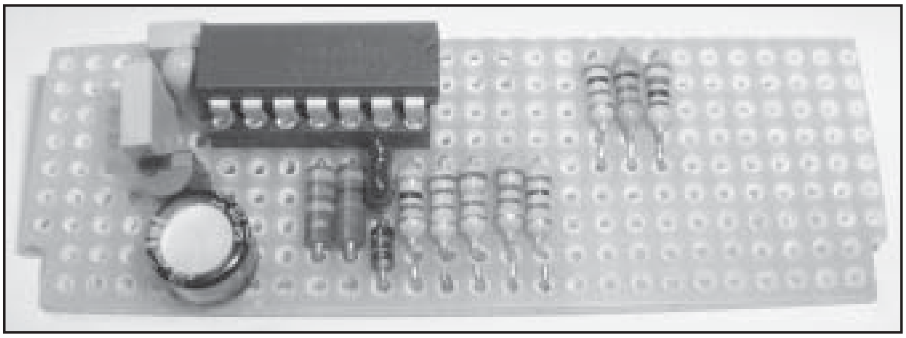


Figure 5 — Top of board.

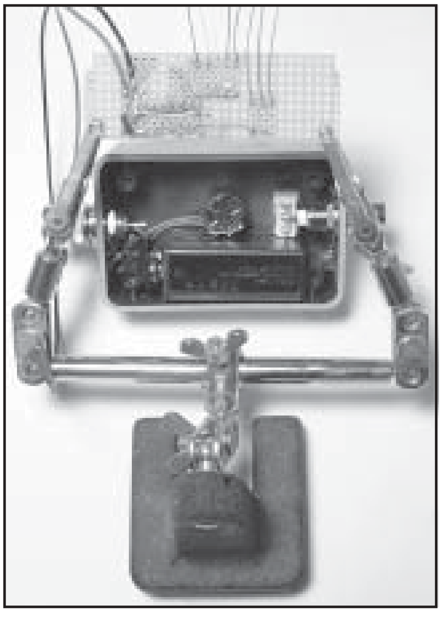


Figure 6 — Bottom of board.

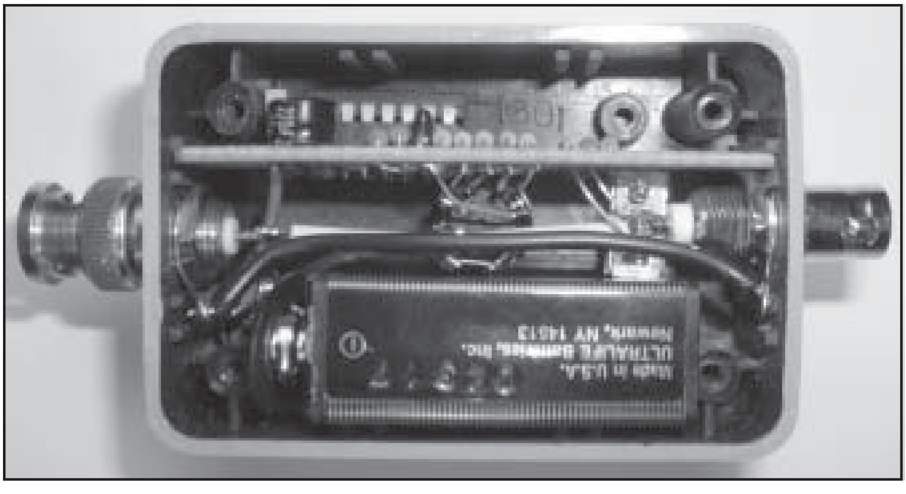


Figure 7 — Inside view.

at the end of the cable, and you can see that the other end is shorted. The reflected pulse is inverted, as predicted by the wave equation. The oscilloscope time base is set to 10 ns per division, and the time between the leading edges of the incident and reflected pulses is 45 ns. Multiplying this by 0.39 ns/ft, the length of this cable was calculated to be 17.55 feet long (a tape measure read 17.5 feet). Figure 10 is the same arrangement, but with an open end. Figure 11 is also an open end, but with a 20 ns pulse; in Figure 12, with a 50 ns pulse, you see the superposition that occurs if the reflected pulse returns before the incident pulse is over. Use whatever pulse width produces the best reflected pulse. As Figure 13 demonstrates, there is no reflected pulse when the cable is terminated in its characteristic impedance.

One Practical Application

A practical application of the *Pizzicato* is shown in Figure 14. This is my Butternut HF6V vertical antenna at the end of 110 feet of direct-bury feed line. Note that the oscilloscope time base has been changed to 100 ns per division, and that the pulse width is 100 ns. The step at 100 feet is the beginning of a length of 75 Ω cable that matches the vertical's radiation resistance of 35 Ω to the feed line.

Table 2
Velocity Factor Tabulation: Practical

Transmission Line	*Velocity Factor*	*Round Trip m / ns*	*Round Trip ft / ns*
Space (vacuum)	1.00	0.15	0.49
Air, 600 Ω open wire	0.98	0.15	0.48
450 Ω twinlead	0.88	0.13	0.43
300 Ω twinlead	0.82	0.12	0.40
Foam coax, hardline	0.80	0.12	0.39
Polyethylene coax	0.66	0.10	0.32

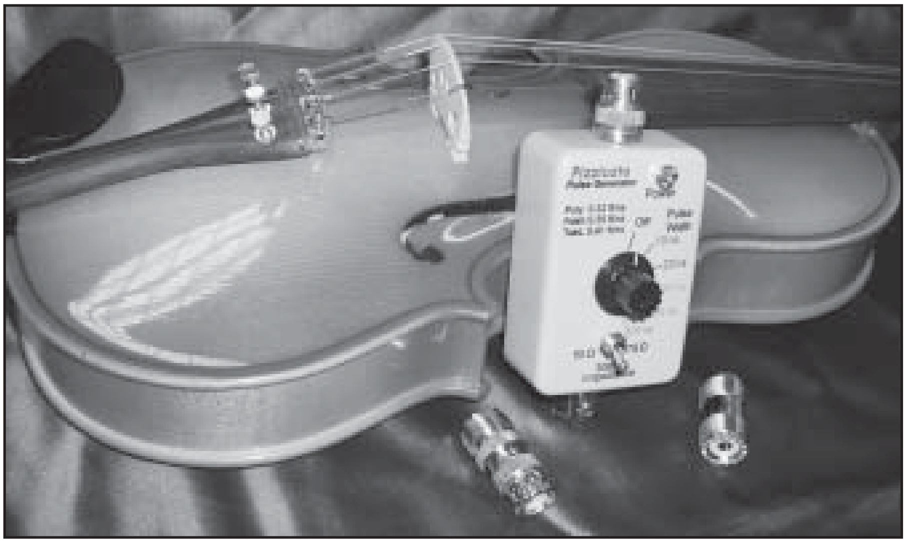


Figure 8 — Front view with violin.

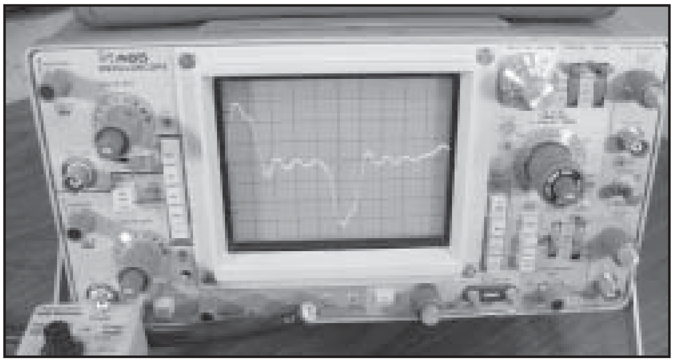


Figure 9 — Shorted 10 ns pulse.

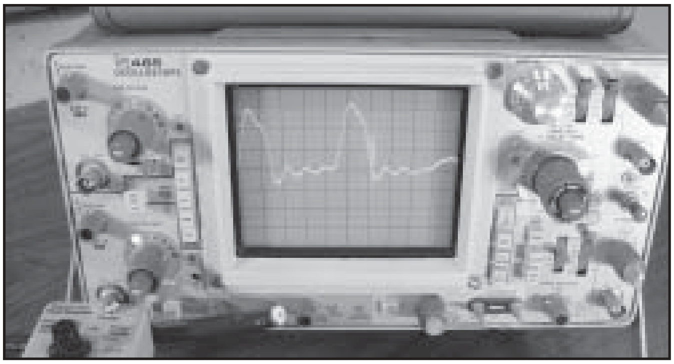


Figure 10 — Open 10 ns pulse.

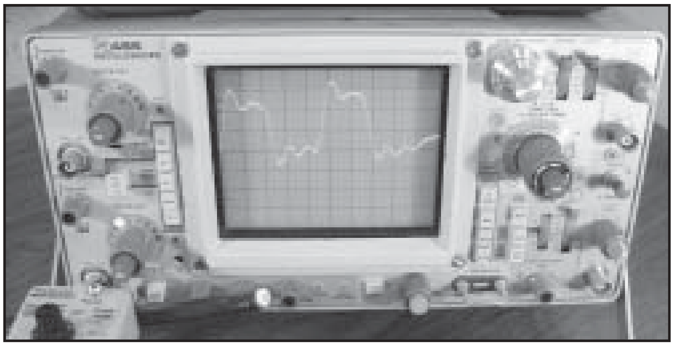


Figure 11 — Open 20 ns pulse.

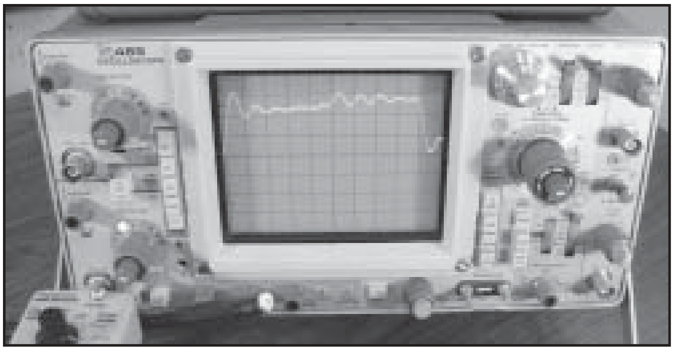


Figure 12 — Open 50 ns pulse.

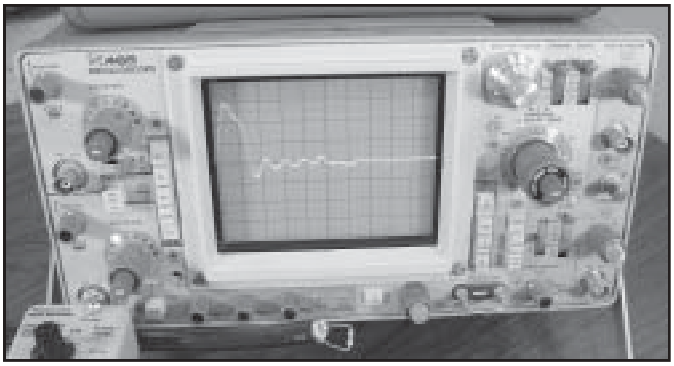


Figure 13 — Terminated with resistor.

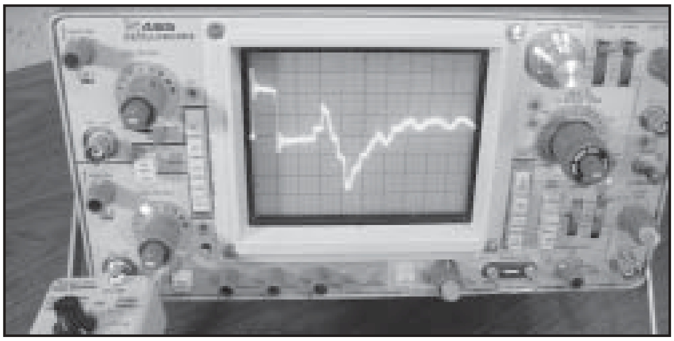


Figure 14 — Vertical antenna.

An S-shape is characteristic of an antenna, and the additional ornamentation is produced by the HF6V's bandswitching capacitors and coils. If the feed line ever develops a flaw, I will know within a foot or so where to start digging!

If your transmission lines have UHF connectors, a UG-255 BNC-to-SO-239 adapter will be a handy accessory, as will an extender made of a PL-258 double-female adapter (see Figure 8) and a length of line with PL-259 connectors. Be careful to support the transmission line so its weight does not overstress the ABS enclosure. Happy plucking with your *Pizzicato*!

Notes

[1] Feynman, Richard Phillips. *The Feynman Lectures on Physics.* Reading, MA: Addison-Wesley, 1965.

[2] Englund, Gunnar. "Build your own 'cable radar,'" *Electronic Design*, October 1, 1998.

Continuously licensed since 1964, Gary Steinbaugh, AF8L, is an ARRL Life Member and a licensed Professional Engineer. He holds a BSEE from Case Institute of Technology, plays (using the word advisedly) many different musical instruments, and is a Certified Flight Instructor. He may be reached at **gsteinbaugh@yahoo.com**. □□

Book Review

Practical RF Circuit Design for Modern Wireless Systems, Vol. 1 and 2

by Rowan Gilmore and Les Besser, Artech House Publishers, ISBN 158053-522-4, $95 each volume.

Browsing one of my electrical engineering trade magazines, my eye caught on the publication notice for this two-volume set. In recent years, the RF designer's world has expanded well beyond what can be captured in a single handbook, leading to a blizzard of books on various specialties, but few that capture "the big picture." Would this be the answer? I borrowed two copies from the library to find out. The two weeks I had the books was obviously not enough time for an exhaustive review, but I believe I was able to assess the books' coverage.

The two volumes divide the RF world into passive circuits and systems (Volume 1) and active circuits and systems (Volume 2). Computer-aided techniques get extensive coverage in each volume and go hand-in-hand with each topic. The books assume that the reader understands the fundamentals of RF design and has access to RF computer-aided design, such as the limited-edition of *Super-Compact* from Compact Software that can be downloaded by hams (**www.arrl.org/ard/**).

Volume 1 starts with the basics, surveys common radio architectures, lays out the Smith chart and s-parameters and then dives into impedance-matching techniques. A section on the techniques used to simulate and optimize RF circuits is followed by a full 70 pages on component models, an often-neglected topic. The compromise is that the next section, on filters and resonant circuits, must cover much ground at a medium to high level. There is so much literature on filters that it would be unreasonable to expect that depth to be reproduced here. The volume concludes with a welcome discussion of the RF characteristics of high-speed digital designs, something that often comes as a surprise to digital designers.

Volume 2 gets into the serious details of RF amplification. It starts with linear RF amplifiers and continues to optimization and comparisons of the different designs. Modeling of active devices and nonlinear circuits is then covered as a detailed survey. Special concerns of high-power amplifier design are presented along with a design example. Oscillators, mixers and multipliers each get an overview. The final section covers several system-level examples, such as mobile telephony, software-defined radios and radio chipsets.

Even at 500 pages per volume, there still isn't enough space to reach a detailed examination of many topics. For example, there aren't enough example problem-and-solution sets to really learn a subject exclusively from these books. However, each section has an extensive set of references for further study. In numerous areas, the authors present a useful set of design equations and principles, but available space prevents them from covering the interactions and sensitivities that inevitably occur in actual designs. For these, readers must do additional research. Nevertheless, there is enough solid foundation material for an engineer to create a basic design and enough references to deal with some secondary considerations. My only complaint is that the graphic style is erratic, as is typical with heavy use of reprinted material. Many of the graphics would benefit as well from a more refined use of line width, style, and density, but these are minor distractions, at worst.

These texts are available through inter-library loan, so you can evaluate them before making the investment. At nearly $100 per volume, these are professional tools. Yet, if you work in the RF field and want a solid handbook to unify your niche references and theoretical textbooks, the set would be a good use of your book budget or a good addition to the company library. — *H. Ward Silver, N0AX, 22916 107th Ave SW, Vashon, WA 98070;* **n0ax@arrl.net** □□