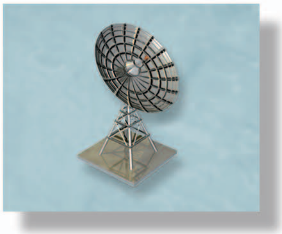

TCC Tidbits

Patents in Microwave Measurement—Nonlinear Transmission Lines

■ **Mark Kahrs**

This column is the first in a series devoted to patents and microwave measurement. Although the patent system is abused and misused, it also offers a path to publish design ideas in addition to journals and conferences. Many times, design ideas and concepts only appear in patents. Therefore, in this column, we will look at how studying patents can inform our knowledge of microwave instrumentation and measurement.

The Nonlinear Transmission Line

The topic of this first column is the nonlinear transmission line (NLTL). Due to their application in pulse compression, NLTLs find use as both harmonic and pulse generators in microwave instrumentation, most recently in products from Anritsu [19].

IMAGE LICENSED BY GRAPHIC STOCK

Early Development

Landauer's papers in 1960 [11], [12] pointed out the importance of dispersion in the creation of shockwaves. Afterward, research was steady (Jäger's work [9] using continuous gallium arsenide (GaAs) lines pushed things along), but it wasn't until Bloom's group at Stanford University produced a crop of Ph.D. dissertations—including Rodwell [22], Van Der Weide [26], and Marsland [13]—that NLTLs were applied to microwave measurement.

Rodwell's first paper appeared in January 1987, but the first patent from Bloom's group was U.S. Patent 5 014 018 [23], filed in October of that year. This initial disclosure by Rodwell describes an integrated NLTL implementation with an LC ladder in GaAs. Another patent was filed just to disclose that the input and output impedances could differ and, therefore, the NLTL could be considered an impedance transformer [4].

Rodwell's work continued with the reimplementation of Grove's sampler [8] (found in U.S. Patent 3 278 763 [7]), using the NLTL as the pulse sharpener. Until the introduction of the NLTL, fast risetime pulses for use as the sampling strobe were limited by the risetime of the tunnel diode and step-recovery diode (SRD) strobe generators. Stanford didn't hesitate to patent the sampler (see U.S. Patents 5 267 020 and 5 378 939, credited to Marsland, Rodwell, and Bloom [14], [15]).

HP's Innovations

Hewlett-Packard (HP) in Palo Alto, California, quickly capitalized on the nearby development by producing the 50-GHz sampler for the 54121T oscilloscope [27]. HP's first patent using this technology came only two months after Rodwell's patent was filed [25]. HP's patent describes how to vary the ratio of dispersion to diode nonlinearity by changing the transmission line length and diode area.

A year later, HP filed the patent for the sampler [24]. It is instructive to compare the two patents: the Stanford patent explicitly describes the use of air bridges, while the HP patent describes (in vague terms) how to implement the balun need to produce balanced sampling strobes.

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But there is considerable overlap. As shown in Figure 1, HP reimplemented Rodwell's reimplementation of the Grove sampler. The last patent filed by HP during this era describes how "stacked" varactors can be used in the transmission line [3].

Further Innovations

Rodwell moved to the University of California, Santa Barbara, and established a group there that extended his dissertation work. Case [5] and Allen [2] both worked on aspects of fabrication, simulation and design. Yu et al. added an RC termination in parallel with a shorted line [28] that reduces the impedance mismatch and, hence, allows low reflections and higher efficiency. Case moved to Hughes Research and quickly patented an extension of his dissertation to cover differential NLTLs [6]. By using antiparallel diodes, this NLTL can compress both rising and falling edges.

NLTLs find use as both harmonic and pulse generators in microwave instrumentation.

PSPL's Work

Picosecond Pulse Lab (PSPL) was founded by National Bureau of Standards researcher Jim Andrews in 1980. Eventually, PSPL expanded to Beaverton, Oregon, and picked off sampling designer A. Agoston from Tektronix. Complete with their own III-V circuit fabricator, PSPL designed and fabricated a sampling head using the NLTL technology from Stanford. The full details of their design can be found in a series of patents beginning with U.S. Patent 6 900 710 [1].

This patent covers an NLTL design with a number of innovations, including the specific use of a nonparallel coplanar waveguide, and also different types of shapes for the transmission line. While it was available, this sampler was the fastest commercial sampler on the market. Figure 2 shows the mask layout of the NLTL-based sampler. The sampling diodes

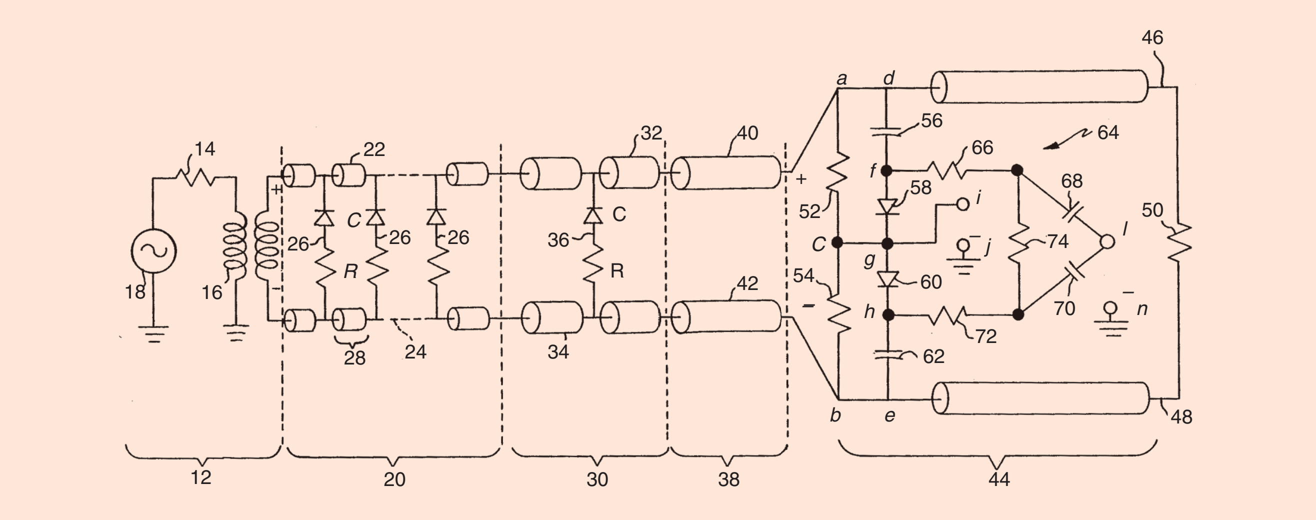

Figure 1. *The schematic of HP's NLTL sampler. (Reproduced from U.S. Patent 4 956 568.)*

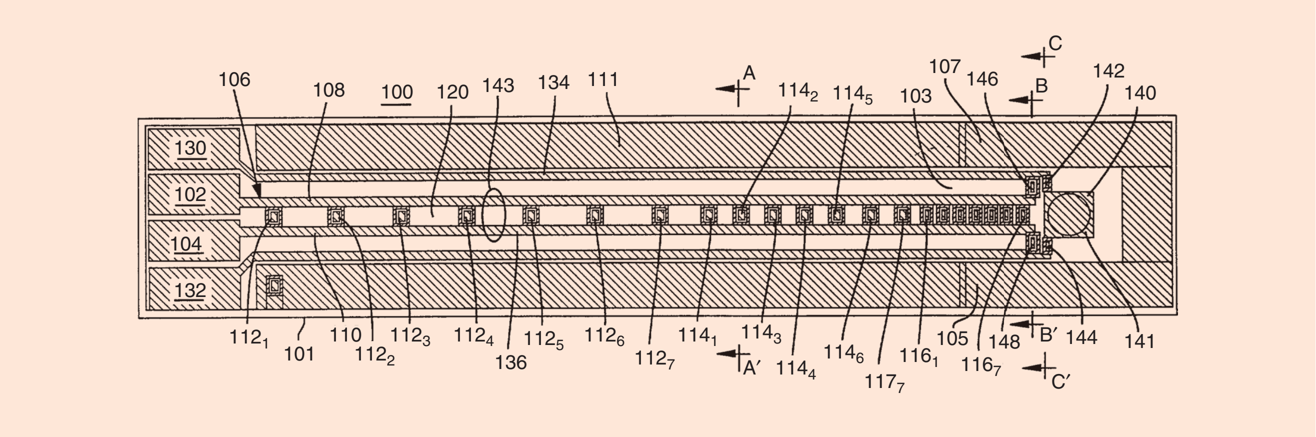

Figure 2. *The mask layout of the PSPL NLTL sampler. (Reproduced from U.S. Patent 7 084 716.)*

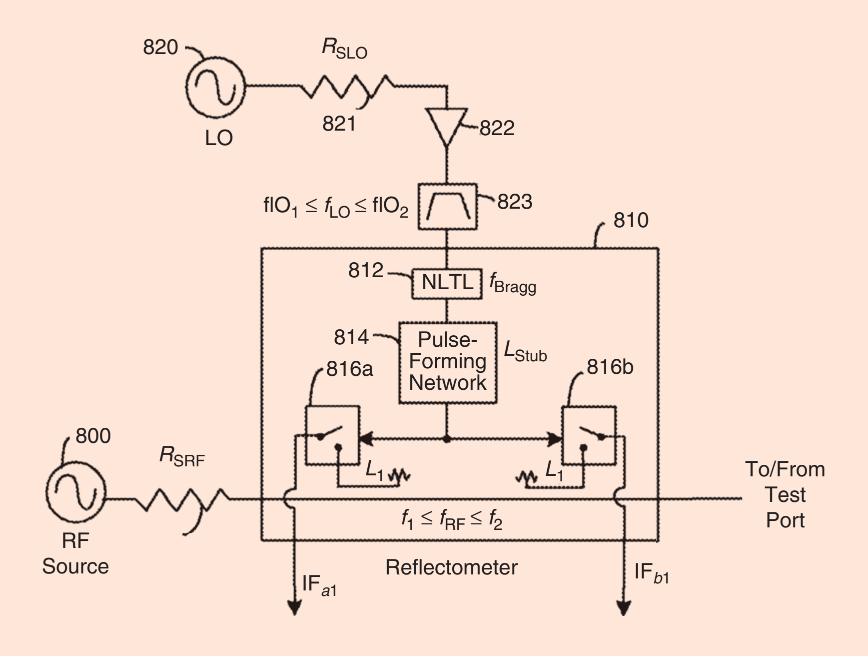

Figure 3. *An example of the use of an NLTL in Anritsu's test set. (Reproduced from U.S. Patent 8 417 189.)*

are at the right-hand edge, near the connection pad.

Pepper, also of PSPL, showed how to bias an NLTL as a comb generator [21]. Included is a very complete discussion of bias generators as a design approach for both integrated and discrete (hybrid) components.

The Late 1990s and Beyond

In the late 1990s, a group at Northrup Grumman was issued a series of patents devoted to NLTL design and application to radio systems. In U.S. Patent 6 690 247, Kintis et al. [10] describe matching the current/voltage characteristics of the diodes in the transmission line to the input waveform. Additionally, the implementation uses a shorting stub to control the output pulse width.

SRDs are commonly used to generate harmonics in vector network analyzers (VNAs). However, the local oscillator input to the SRD is fundamentally limited due to the transit time of the diode. Additionally, the high harmonic order needed for millimeter-wave measurements will result in an increased noise figure.

Anritsu showed interest in the use of NLTL starting in 2003, with Noujeim's patent [17] describing ways to reduce shock-wave-to-surface-wave coupling. In particular, the patent describes the use of a coplanar strip over a thickened substrate.

Noujeim also showed that, instead of distributing the output of a SRD to each of the samplers, it is possible to integrate an NLTL with each sampler, thereby reducing the leakage from each channel and increasing the interchannel isolation [20].

Finally, Noujeim and Martens illustrate how an NLTL can be applied in a VNA system in U.S. Patent 8 417 189 [18] (an example is shown in Figure 3). The patent offers three methods for extending the range of a VNA using an NLTL:

1) changing the fall time of a shock-line output voltage waveform by varying the number of diodes in the shockline while also changing the spacing between diodes
2) changing the structure of the pulse-forming network
3) changing the local oscillator frequency.

Additionally, Noujeim and Martens show how to extend the dynamic range by controlling the diode bias in U.S. Patent 8 718 586 [16].

Conclusions

As discussed here, patents play a critical role in microwave engineering design and implementation outside of the academic applications described in conferences and journals. Once upon a time, it was very difficult to track down the intellectual threads behind an instrument; now, due to the search tools available on the Internet, it is easy enough for any curious engineer to do so.

Acknowledgment

My thanks to Prof. Mark Rodwell for providing back stories on the history of microwave use of the NLTL.

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