Distributed Broad-Band Frequency Translator and Its Use in a 1–3-GHz Coherent Reflectometer

Prayoot Akkaraekthalin, *Student Member, IEEE*, Scott Kee, and Daniel W. van der Weide, *Member, IEEE*

***Abstract*—We present the first frequency translator based on a nonlinear transmission line (NLTL) phase shifter and demonstrate its application in a coherent reflectometer, giving performance comparable to a commercial network analyzer. Rather than forming shock waves on the NLTL with large signal excitation, we use its voltage-variable delay together with both amplitude and phase linearization to modulate the phase of a small 0.5–3.0-GHz microwave signal. The resultant single sideband modulator exhibits >45 dBc carrier and spurious suppression. This new approach has significant applications in both instrumentation and sensing, particularly because it offers a clear path toward complete integration of a coherent measurement system.**

***Index Terms*—Frequency translator, microwave measurements, nonlinear transmission line.**

I. Introduction

As THE capabilities of communication, computation, and radar systems continue to rise, the ability to evaluate them must always stay one step ahead. Conventional logic systems are reaching clock rates in the 1-GHz regime, while new devices and architectures—both for computation and wide-band radar—aim for 100-GHz operation, so there is a clear need for instruments to test these systems, particularly in the field. Furthermore, new sensors using micro- and millimeter-wave reflection and transmission often depend on coherent generation and detection of these signals.

What has been less clear is the approach to develop such instrumentation. Commercial vector network analyzers (VNA's) are very accurate and can now measure network parameters to 100 GHz, but their bulk, expense, and narrow instantaneous bandwidths limit their use to the laboratory and to linear devices and systems. Short-pulse lasers have been proposed and pursued by several groups using a wide variety of methods to test ultrafast or wide-band devices and circuits, but laser-based approaches will not likely become portable, low-power, low-cost solutions for measuring 1–100-GHz signals.

A promising alternative to these short-pulse laser systems is a purely electronic one using picosecond pulses from integrated circuit (IC) nonlinear transmission lines (NLTL's) [1]–[4]. This is a much more design- and technology-intensive approach than the laser-based systems, limiting the number of groups pursuing it. One of the most significant barriers to their widespread deployment, however, has been their need for coherent (phase-locked) microwave synthesizers to drive them, placing their total bulk and expense on par with the laser systems. Similar economic concerns drive the design of commercial VNA's: they rely on only one synthesized source and use a sampling detector, rather than use two sources and a mixer, trading dynamic range for lower cost.

We offer a new solution that can enable complete integration of wide-band network analyzers, directly addressing the need for instruments to characterize 100-GHz devices, circuits, and systems, as well as the growing opportunities for sensors in this regime. Combining a NLTL phase shifter with serrodyne (sawtooth) modulation results in a frequency translator that can use an inexpensive—ultimately integrated—microwave source to coherently convert a wide-band microwave signal directly to baseband. This invention, coupled with improved directional sampling circuits [1], [3], could enable high-performance, inexpensive, and field-capable 100-GHz vector network analysis, as well as several other new military and commercial applications which benefit from a monolithic coherent generation/detection system [5]–[8], such as terahertz reflectometers. This approach is the first to present a clear path to complete integration of a coherent micro- and millimeter-wave measurement system.

II. Background

Synchronous microwave measurements require two phase-coherent but frequency-offset signals. These can be achieved using a variety of techniques, including optoelectronic "pump-probe" [9], [10] and electronic mixing with phase-locked synthesizers [6], as well as with harmonic sampling as employed in commercial microwave instruments. None of these methods has yet been monolithically integrated, although the pump-probe technique of scanning the phase of one optical beam against that of another might one day be realized in a micro-electrical-mechanical system (MEMS) for periodic frequency translation.

Thus, in a fashion analogous to a Michelson interferometer, synchronous measurements can be made using a single source whose power is split into two arms, the phase of one arm linearly delayed with respect to the other, then the two arms recombined for heterodyning (Fig. 1). Linear phase shifting with time is equivalent to frequency translation. Frequency

Manuscript received April 8, 1998; revised September 1, 1998. This work was supported by the Office of Naval Research through the Young Investigator Program, the National Science Foundation through the PECASE award, by the Federal Aviation Administration, and by Ford Motor Company through a University Research Award. The work of P. Akkaraekthalin was supported by the Ministry of Science, Technology and Environment, Royal Thai Government.

The authors are with the Department of Electrical and Computer Engineering, University of Delaware, Newark, DE 19716-3130 USA.

Publisher Item Identifier S 0018-9480(98)09213-8.

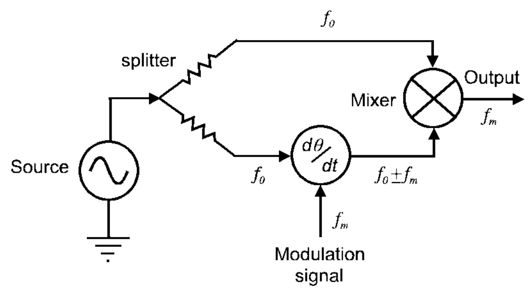


Fig. 1. Block diagram of frequency translator application. Phase shifter is serrodyne modulated at f_m and output of mixer (right) is a sinusoid at frequency f_m.

translators are used in a variety of microwave systems but take on special importance when they can be monolithically integrated. Integrated frequency translation enables synchronous down-conversion in a compact low-cost system and can form the basis for a wide range of useful tools, such as network and spectrum analyzers [1], [3], [11], sampling receivers, and electronic terahertz systems [6].

An ideal frequency translator should change the original frequency f_o of a signal by a modulation frequency f_m by applying a phase $\theta = 2\pi f_m t$ that varies linearly with time, giving an output $V_0 = \sin(2\pi f_o t + 2\pi f_m t) = \sin 2\pi(f_o + f_m)t$. This function can be realized in a continuous fashion using a rotary phase shifter driven at a constant rate such that $\partial\theta/\partial t = f_m$ [5]. An advantage of this approach is that the phase jitter between the two signals can be very low (since it depends largely on the modulator) even if a relatively unstable source is used.

This function can also be realized using an ideal sawtooth modulation of θ which varies the phase linearly between zero and 360 degrees, then flies back to zero instantaneously—serrodyne modulation [12], [13]. Although serrodyne modulation was already being explored in the 1950's, these implementations primarily used binary switching of fixed-phase delay elements to approximate a sawtooth with a coarse staircase. New methods of integrating fixed-delay transmission line segments, switches, and drivers have enabled 6–18-GHz digital, or *discrete*, phase shifters, which, when serrodyne modulated, have given 22 dB of carrier and spurious suppression [14].

In principle, any *continuous* phase shifter capable of 360° operation could be modulated with a sawtooth waveform to realize a serrodyne frequency translator, but only techniques amenable to monolithic integration are of interest to us here. In particular, monolithic continuous, or analog, phase shifters are usually realized by integrating hybrid couplers with variable capacitance or gain arising from diodes or transistors. The couplers produce in-phase and quadrature components of the input signal that are modified by the active devices and recombined to give continuous phase shifts. Using Lange couplers, bandwidths of up to an octave for phase shifts of 160° have been achieved in these monolithic devices [15], while for single-frequency (24 GHz) operation, a full 360° serrodyne frequency translator has been realized in monolithic form [16].

III. Frequency Translation with a NLTL Phase Scanner

A. Principles of NLTL's

In order to achieve *broad-band* (multi-octave) frequency translation, however, a low-Q structure is required. To reduce losses, the structure should be distributed rather than simply resistive. For monolithic integration, varactor diodes rather than ferromagnetic components should be the variable-phase elements [17]. When driven in small-signal mode, the NLTL satisfies all these requirements. Consequently, the same process technology can provide both small-signal phase modulation for frequency translation in one NLTL while enabling wavefront compression for harmonic multiplication and time-domain metrology in another NLTL on the same substrate. The combination of these elements is a new and central feature of our approach.

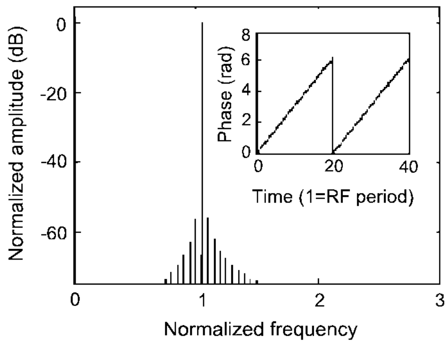
While the use of the NLTL structure as a phase modulator was mentioned a decade ago [18] and has surfaced more recently in the literature [19], [20], it has only been in the context of phase shifting, not frequency translation. Here we demonstrate the first frequency translator based on the NLTL used as a phase modulator rather than in its customary role as a picosecond and subpicosecond pulse generator [4]. Using both serrodyne (sawtooth) and triangle-wave modulation, we demonstrate coherent downconversion of gigahertz signals to baseband at frequencies limited only by the speed of the arbitrary waveform generator we used for modulation. We go on to apply this new technique in a coherent reflectometer working in the 1–3-GHz band, its low end limited only by availability of a suitable directional coupler. This work indicates that single-chip low-cost coherent microwave measurement systems can be realized.

NLTL's have been built both as discrete and as integrated circuits. They exhibit voltage-dependent delay that can be exploited for phase scanning and frequency conversion, as well as for their more familiar use as wavefront compressors. These circuits consist of series inductors (or sections of high-impedance transmission line) with varactor diodes periodically placed as shunt elements. On this structure, the phase velocity v_p is modulated by the diode capacitance $\Delta v_p = 1/\sqrt{LC(V)}$ where L is the inductance and $C(V)$ the sum of the diode and parasitic capacitance of the line, all per unit length [2].

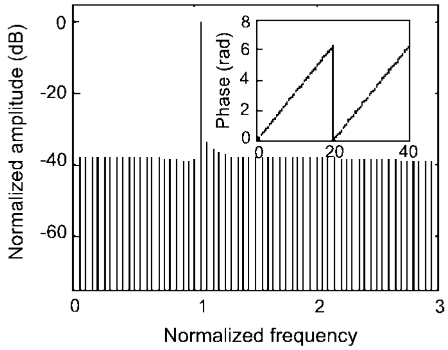
In contrast to most active circuits, the process for fabricating NLTL's is comparatively simple, involving only diodes, transmission lines, capacitors, and resistors. This process also allows integration of diode sampling bridges [1] which can themselves be strobed with the pulsed output waveform of an NLTL, enabling a complete single-chip coherent generation and measurement system, provided there is a source of coherent excitation signals.

B. Serrodyne Modulation of NLTL's

While our approach offsets one microwave frequency from another by scanning the phase of an NLTL at the offset frequency, this offset cannot be arbitrarily large. We have simulated a serrodyne frequency translator under a variety



(a)



(b)

Fig. 2. Simulations of serrodyne frequency translator with translated spectrum and modulation waveforms (insets) for $f_o/f_m = 20$ and flyback duration of (a) 0.1% and (b) 1%. Note increasing sideband and spurious levels with slower flyback time.

of modulation conditions to observe how the NLTL would respond at increasingly higher modulation rates. In Fig. 2, we show two representative results of the simulation, pointing out one limitation to achieving high-speed modulation: as the retrace transient ("flyback") time becomes increasingly significant in the period of the sawtooth waveform, sidebands become more prominent.

For example, to build an ultrawide-band 500-MHz modulator with the near-ideal results of the upper half of Fig. 2 would require a 2-ps flyback in the 2-ns period. One approach we could use to achieve such ultrawide-band performance would be, in fact, to use another NLTL to modulate the frequency translator itself, since the NLTL output waveform is a sawtooth with a <2-ps falling edge. Another approach would be to build a nonlinear control system to achieve minimum transition time during flyback.

Most systems, however, do not require such high frequency modulation, though carrier and spurious suppression remain important. An alternative to circuit-based approaches is to allow a longer flyback time and pause the baseband digitizing circuitry and/or fast Fourier transform (FFT) calculation, allowing the circuit to fly back while ignoring the resultant spurious products that are generated (only) during this time. A similar approach we demonstrate below is to use triangle-wave phase modulation and run the FFT forward during one cycle and backward during the second, eliminating the retrace transient entirely.

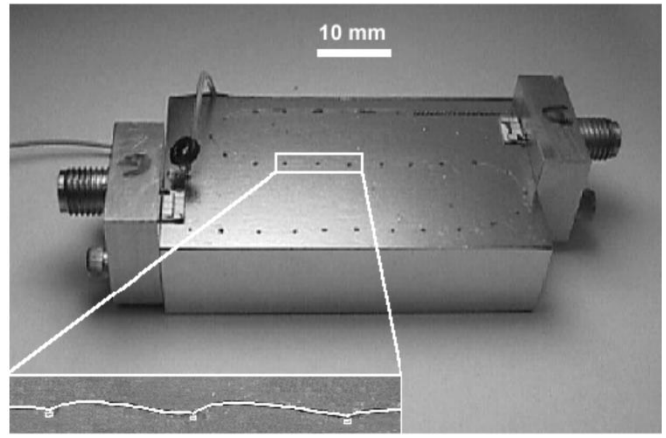


Fig. 3. Brass block assembly of nonlinear transmission line phase shifter. Inset shows detail of bond-wire interconnnection of Si Schottky diodes.

Sidebands also result from the staircase modulation of the phase shifter. From a Fourier series analysis of a stepped-phase frequency translator [13], the normalized spectral output amplitude of the translated radio frequency (RF) signal can be expressed as

$$|d_n^{\pm}| = \frac{\sin\frac{\pi}{N}}{(kN \pm 1)\frac{\pi}{N}} \approx \frac{1}{kN \pm 1} \tag{1}$$

where N is the number of steps in the staircase, $n = 1 \pm kN$ is the spectrum number (the number of modulation frequency increments away from the input frequency f_o), $\pm$ indicates the upper or lower sideband, and k is an integer from 0 to ∞. If $(n \pm 1)/N \neq k$, $e_n^{\pm} = 0$ (although we in fact do measure components in this regime as shown in Fig. 8). If $(n \pm 1)/N = k$, there will be an output at a harmonic of the modulation frequency f_m [14], and for these components we measured >50 dBc suppression at 1.0 GHz, as shown in Fig. 8. In this equation, the sideband suppression level with respect to the desired output can be determined at any harmonic k. Using $k = 1$, the minimum sideband suppression level is 48.1 dBc for an 8-bit digital frequency translator ($N = 256$). The sideband suppression level will be improved by ~6 dB for every added bit. In this work, we used a 12-bit analog-to-digital converter as an arbitrary waveform generator driving the NLTL phase shifter, so the flyback transient primarily limited the harmonic performance.

C. Experimental Results

To demonstrate our approach, we built a scale-model NLTL phase shifter on a brass block (Fig. 3). The circuit consists of 30 abrupt junction diodes ($C_{j0} = 2$ pF) with 4.6-mm interval spacing for the first section and 20 abrupt junction diodes ($C_{j0} = 0.8$ pF) with 0.6-mm spacing for the second [21]. Measurements of phase delay and transmission loss compared well with models done in both PSPICE and Libra. This circuit was able to achieve >2 ns delay, yet was usable beyond 3 GHz. For comparison, single GaAs IC NLTL's can achieve ~160 ps delays [4], [22] with higher usable frequencies; they can also be cascaded for additional delay.

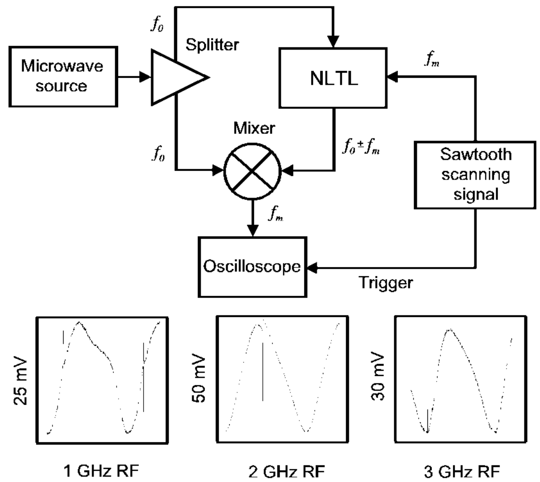


Fig. 4. (a) Experimental setup for serrodyne frequency translation with NLTL phase shifter. (b) Beatnote oscilloscope trace shows initial uncompensated results from serrodyne NLTL frequency translator at 1.0, 2.0, and 3.0 GHz using 7-kHz modulating waveform. Note flyback transients.

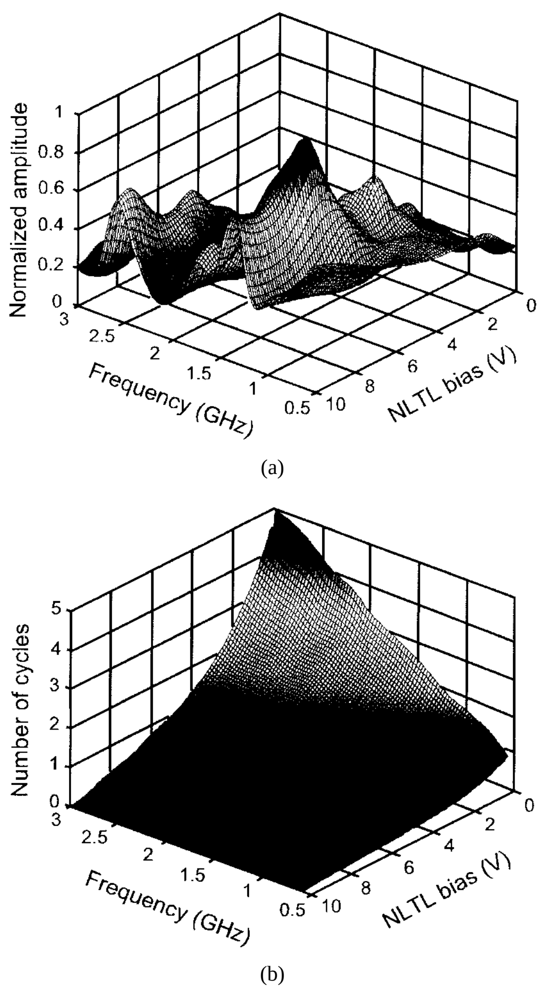


Fig. 5. (a) Amplitude and (b) phase variation of NLTL transmission coefficient over bias and frequency.

As shown in Fig. 4, we first built a simple system with no amplitude or phase compensation to demonstrate the principle of serrodyne modulation with this structure. Although the circuit works as anticipated when modulated at f_m through 2π radians at the fundamental microwave frequency f_o, both distortion in the output waveform and the flyback transient are apparent.

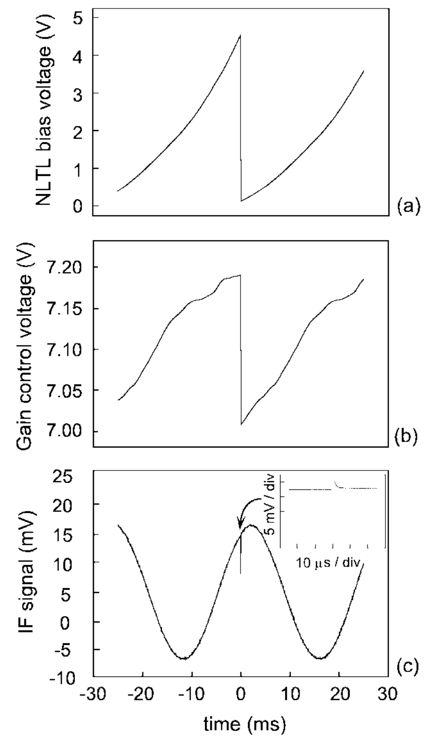


Fig. 6. Measurement at $f_0 = 1$ GHz and $f_m = 35$ Hz using sawtooth scanning signals: (a) scanning signal with phase compensation, (b) gain control voltage with amplitude compensation, and (c) output voltage after mixer.

We then made comprehensive measurements of the magnitude and phase of the NLTL transmission coefficient versus bias and frequency, as shown in Fig. 5. With this data in look-up tables, we implemented a phase linearization and amplitude compensation scheme using a gain-controlled amplifier (HP IVA 14 208) for amplitude and the 12-bit D/A for phase. We measured the beat note between the original microwave signal and its frequency-shifted version using both serrodyne and triangle-wave modulation. Both methods gave nearly pure sinusoidal results, but the serrodyne version exhibited a flyback transient (Fig. 6), while we could reconstruct the output sinusoid without this transient by using triangle-wave modulation by time-reversing each second cycle of the output (Fig. 7).

In spite of the cleaner time-domain appearance of the triangle-wave modulated output, when driven at 0 dBm the serrodyne version exhibited >45 dB of carrier and harmonic suppression compared to ~35 dB for the triangle wave. Fig. 8 shows the microwave spectrum, but the downconverted spectrum also showed this level of harmonic suppression. In the future, we can address the shortfall of the triangle-wave modulation with more careful waveform reconstruction.

IV. Reflectometer

A conventional microwave reflectometer consists mainly of a microwave source, a dual directional coupler, and detectors. The ratio of the reflected wave and incident wave is the

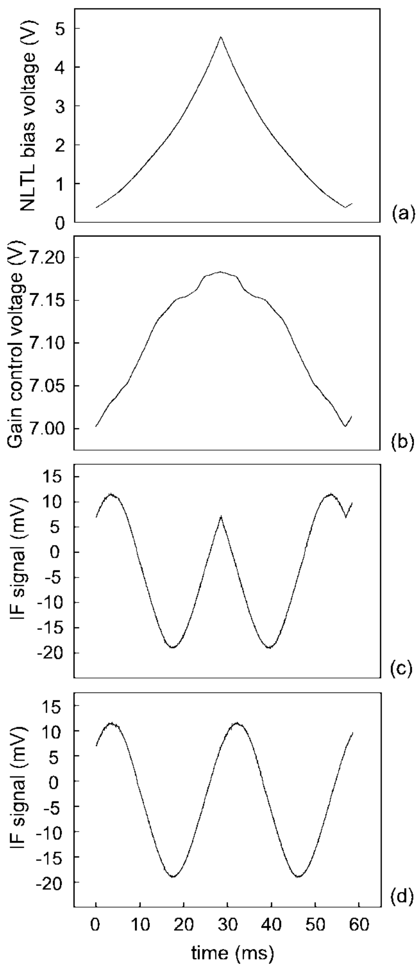


Fig. 7. Measurement at $f_0 = 1$ GHz and $f_m = 35$ Hz using triangle-wave scanning signals. (a) Scanning signal with phase compensation. (b) Gain control voltage with amplitude compensation. (c) Output voltage after mixer and amplifier. (d) Final output voltage after time-reversing the second cycle.

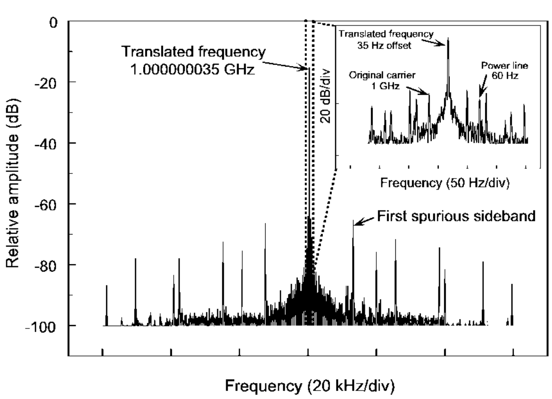


Fig. 8. Microwave spectrum showing >45 dBc carrier suppression and >50 dBc spurious sideband suppression.

voltage reflection coefficient of the device under test (DUT). Reflectometers form the core of microwave network analyzers and are typically based on power sensing (using diodes or bolometers) or coherent sampling front ends.

Several techniques have been proposed to address the need for accurate reflectometry [23]–[25]. Using standard loads

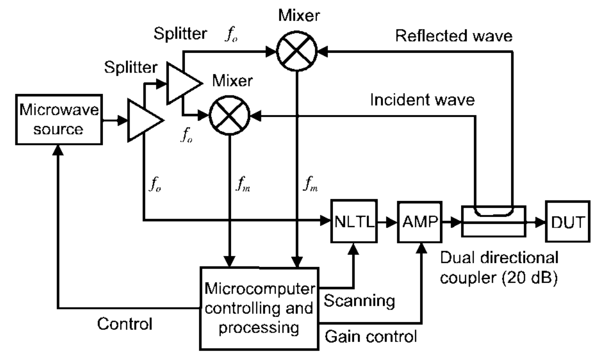


Fig. 9. Block diagram of compensated NLTL phase scanner for frequency translation used in a calibrated reflectometer. Microwave source is an HP 83620A synthesizer; directional coupler is an HP 11692D.

to calibrate a conventional reflectometer has been proposed by Hollway and Somlo [26]. This technique uses no critical components and requires no tuning adjustments, so it is simple, accurate, and useful for automatic operations. The disadvantage of this technique is that the phase of the reflection coefficient cannot be measured because the detectors yield just the amplitude or power of the microwave signals. In order to obtain the phase, additional couplers or hybrids and detectors must be added. This measurement scheme was introduced by Cohn and Weinhouse [27], followed by Hoer [28], then developed into a six-port reflectometer (requiring four detectors) by Engen [29]–[31], and a seven-port reflectometer (requiring five detectors) by Cullen and Belfort [32].

Meanwhile, heterodyne reflectometers as employed in modern commercial network analyzers use sampling front ends, which improve upon the dynamic range limitations of the six-port approaches. These could be further improved, however, by use of mixers in the front end, except that the expense of an additional microwave source is prohibitive. Homodyne reflectometers [33], [34], while not commercially available, bear the strongest similarity to the architecture we use here in that they usually employ a variable-phase and reference arm derived from a single source, and they use balanced mixers as detectors. Their dynamic range is limited, however, by dc detection.

We constructed a reflectometer using the NLTL frequency translator to provide high accuracy, high stability, and a potentially low-cost system (Fig. 9). This technique can be readily extended to a two-port network analyzer.

If we assume there are no reflections from detection ports to the main line of the dual directional coupler, we obtain the simplified signal flow graph of the reflectometer (Fig. 10), where A and B are detection factors. If the microwave source is matched, $\Gamma_S = 0$, and if the dual directional coupler is symmetrical, $S_{31} = S_{42}$ and $S_{32} = S_{41}$. Solving the simplified signal flow graph will provide the ratio of $P_{\rm ref}$ and $P_{\rm inc}$

$$P = \frac{P_{\rm ref}}{P_{\rm inc}} = \frac{B}{A} \cdot \frac{S_{32}(1 - S_{22}\Gamma_L) + S_{21}S_{31}\Gamma_L}{S_{31}(1 - S_{22}\Gamma_L) + S_{21}S_{32}\Gamma_L}. \tag{2}$$

We use three commercial 3.5-mm coaxial standards to calibrate the reflectometer. From the above equation, we substitute $P = P_M$ for matched load $(\Gamma_L = 0)$, $P = P_S$ for a short circuit $(\Gamma_L = -1)$, $P = P_O$ for an open circuit

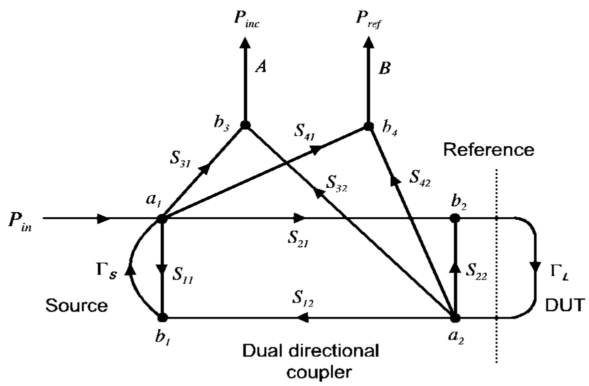


Fig. 10. Signal flow diagram for reflectometer system.

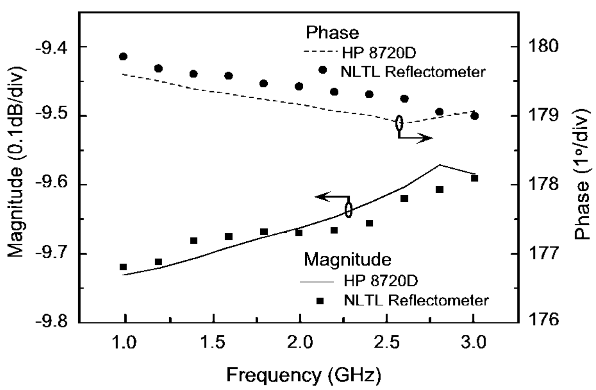


Fig. 11. Results from measurement of a 25-Ω load.

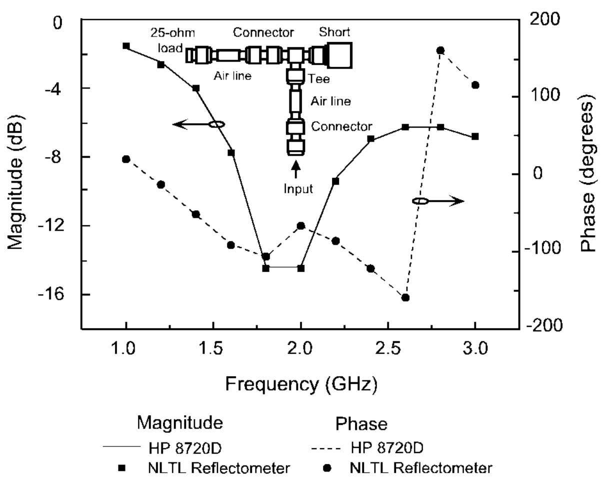


Fig. 12. Results from measurement of arbitrary load (diagram in inset).

$(\Gamma_L = 1)$, and $P = P_L$ for an arbitrary load or DUT. Solving the equation for these conditions yields the measured reflection coefficient

$$\Gamma_L = \frac{(P_M - P_L)(P_0 - P_S)}{(P_M + P_L)(P_0 + P_S) - 2(P_o P_S + P_M P_L)}. \quad (3)$$

Theoretically, using this error calibration technique, the directivity of the dual directional coupler need not be very high, and the reflectometer can be employed for accurately measuring small reflections.

We used the calibrated reflectometer of Fig. 9 to measure the complex reflection coefficient of two different DUT's. The measurement of a 25-Ω load from 1 to 3 GHz is shown in Fig. 11 compared to the result from an HP 8720D network analyzer, where we see a maximum 0.03-dB offset in magnitude and agreement in phase within 0.5°. We also measured an arbitrary load with larger variations in reflection coefficient against the HP 8720D, as shown in Fig. 12. Finally, we measured equivalent values (−80 dB) for return loss on a 50-Ω calibration standard using both instruments.

V. CONCLUSIONS

We have shown that modulated NLTL frequency translators are viable candidates for integration with NLTL pulse generators and diode sampling bridges, enabling for the first time the foundation of a complete monolithic wide-band microwave and millimeter-wave network analyzer system. We extended this approach to building a 1–3-GHz reflectometer with performance comparable to a commercial instrument. While this technique lays a promising foundation for inexpensive coherent microwave instrumentation, it can be further extended to other micro- and millimeter-wave sensors, such as handheld reflectometers operating in the terahertz regime for applications such as demining as well as sensing gasses, nonmetallic weapons, and explosives.

REFERENCES

[1] R. A. Marsland, C. J. Madden, D. W. van der Weide, M. S. Shakouri, and D. M. Bloom, "Monolithic integrated circuits for mm-wave instrumentation," presented at 12th Annual GaAs IC Symposium, New Orleans, LA, 1990.

[2] M. J. W. Rodwell, M. Kamegawa, R. Yu, M. Case, E. Carman, and K. S. Giboney, "GaAs nonlinear transmission lines for picosecond pulse generation and millimeter-wave sampling," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1194–204, 1991.

[3] R. Y. Yu, M. Reddy, J. Pusl, S. T. Allen, M. Case, and M. J. W. Rodwell, "Millimeter-wave on-wafer waveform and network measurements using active probes," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 721–729, 1995.

[4] D. W. van der Weide, "Delta-doped Schottky diode nonlinear transmission lines for 480-fs, 3.5-V transients," *Appl. Phys. Lett.*, vol. 65, pp. 881–883, 1994.

[5] D. W. van der Weide, J. S. Bostak, B. A. Auld, and D. M. Bloom, "All-electronic free-space picosecond pulse generation and detection," *Electron. Lett.*, vol. 27, pp. 1412–1413, 1991.

[6] ——, "All-electronic generation of 880 fs, 3.5 V shockwaves and their application to a 3 THz free-space signal generation system," *Appl. Phys. Lett*, vol. 62, pp. 22–24, 1993.

[7] Y. Konishi, M. Kamegawa, M. Case, Y. Ruai, S. T. Allen, and M. J. W. Rodwell, "A broadband free-space millimeter-wave vector transmission measurement system," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1131–1139, 1994.

[8] J. S. Bostak, D. W. van der Weide, D. M. Bloom, B. A. Auld, and E. Özbay, "All-electronic terahertz spectroscopy system with terahertz free-space pulses," *J. Opt. Soc. Amer. B*, vol. 11, pp. 2561–2565, 1994.

[9] J. Valdmanis, M. C. Nuss, P. R. Smith, K. D. Li, and S. S. Pei, "1 THz bandwidth probing of devices and integrated circuits," presented at Int. Electron Devices Meeting, Washington, DC, 1987.

[10] K. J. Weingarten, M. J. W. Rodwell, and D. M. Bloom, "Picosecond optical sampling of GaAs integrated circuits," *IEEE J. Quantum Electron.*, vol. 24, pp. 198–220, 1988.

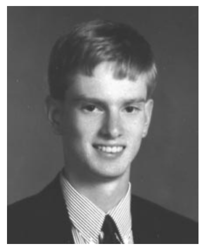
[11] R. Y. Yu, M. Kamegawa, M. Case, M. Rodwell, and J. Franklin, "A 2.3-ps time-domain reflectometer for millimeter-wave network analysis," *IEEE Microwave Guided Wave Lett.*, vol. 1, pp. 334–336, 1991.

[12] J. S. Jaffe and R. C. Mackey, "Microwave frequency translator," *IEEE Trans. Microwave Theory Tech.*, vol. 13, pp. 371–378, 1965.

[13] G. Klein and L. Dubrowsky, “The DIGILATOR, a new broadband microwave frequency translator,” *IEEE Trans. Microwave Theory Tech.*, vol. 15, pp. 172–179, 1967.
[14] S. Mazumder and C. Isham, “Frequency translation by phase shifting,” *Appl. Microwave Wireless*, vol. 7, pp. 59–66, 71, 1995.
[15] S. K. Koul and B. Bhat, *Microwave and Millimeter Wave Phase Shifters, Vol. 2*. Boston, MA: Artech House, 1991.
[16] S. Lucyszyn, I. D. Robertson, and H. Aghvami, “24 GHz serrodyne frequency translator using a 360 degrees analog CPW MMIC phase shifter,” *IEEE Microwave Guided Wave Lett.*, vol. 4, pp. 71–73, 1994.
[17] S. K. Koul and B. Bhat, *Microwave and Millimeter Wave Phase Shifters, Vol. 1*. Boston, MA: Artech House, 1991.
[18] M. J. W. Rodwell, D. M. Bloom, and B. A. Auld, “Nonlinear transmission line for picosecond pulse compression and broadband phase modulation,” *Electron. Lett.*, vol. 23, pp. 109–110, 1987.
[19] P. Celka, M. J. Hasler, and A. Azizi, “Analysis and linearization of a broadband microwave phase modulator using Volterra system approach,” *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 2246–2255, 1996.
[20] W. M. Zhaug, R. P. Hsia, C. Liang, G. Song, C. W. Domier, and N. C. Luhmann, Jr., “Novel low-loss delay line for broadband phased antenna array applications,” *IEEE Microwave Guided Wave Lett.*, vol. 6, pp. 395–7, 1996.
[21] D. W. van der Weide, “A YIG-tuned nonlinear transmission line multiplier,” presented at the MTT-S Int. Microwave Symp., Atlanta, GA, 1993.
[22] D. W. van der Weide and P. Brunemeier, “Pulse-doped GaAs nonlinear transmission lines for 630 fs, 1 V shockwaves,” presented at Ultrafast Phenomena IX, Dana Point, CA, 1994.
[23] G. F. Engen and R. W. Beatty, “Microwave reflectometer techniques,” *IRE Trans. Microwave Theory Tech.*, vol. 7, pp. 351–355, 1959.
[24] F. C. DeRonde, “A precise and sensitive X-band reflectometer providing automatic full-band display of reflection coefficient,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-13, pp. 435–440, 1965.
[25] D. L. Hollway, “The comparison reflectometer,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-15, pp. 250–259, 1967.
[26] D. L. Hollway and P. I. Somlo, “A high-resolution swept-frequency reflectometer,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, 1969.
[27] S. B. Cohn and N. P. Weinhouse, “An automatic microwave phase measurement system,” *Microwave J.*, vol. 7, pp. 49–56, 1964.
[28] C. A. Hoer, “The six-port coupler: A new approach to measuring voltage, current, power, impedance, and phase,” *IEEE Trans. Instrum. Meas.*, vol. IM-21, pp. 466–470, 1972.
[29] G. F. Engen, “The six-port reflectometer: An alternative network analyzer,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 1075–1080, 1977.
[30] ——, “An improved circuit for implementing the six-port technique of microwave measurements,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 1080–1083, 1977.
[31] ——, “A (historical) review of the six-port measurement technique,” *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 2414–2417, 1997.
[32] A. L. Cullen and A. J. Belfort, “Seven-port millimeter-wave reflectometer,” *Electron. Lett.*, vol. 21, pp. 120–121, 1985.
[33] R. J. King, *Microwave Homodyne Systems*. London, U.K.: Peregrinus, 1978.
[34] O. Ostwald and B. Schiek, “Network analysis by phase-modulated homodyne detection,” *IEEE Trans. Instrum. Meas.*, vol. IM-30, pp. 152–154, 1981.

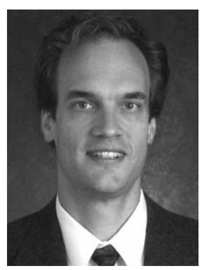
Prayoot Akkaraekthalin (S'98) received the B.Eng. and M.Eng. degrees in electrical engineering from King Mongkut Institute of Technology, North Bangkok (KMITNB), Thailand, in 1986 and 1990, respectively, and recently received the Ph.D. degree from the University of Delaware, Newark.

From 1986 to 1988, he worked in the Microtek Laboratory, Thailand, as a Research and Development Engineer. In 1988, he joined the Department of Electrical Engineering, KMITNB, as an instructor. His research interests are in the areas of microwave circuit design and optoelectronic and telecommunication.



Scott Kee was born in Albany, OR, in 1976. He received the B.E.E. degree in electrical engineering from the University of Delaware, Newark, in 1998. He is currently working toward the master's degree at the California Institute of Technology, Pasadena.

His research interests include high-frequency and microwave design, analog electronics, and electronics for practicing musicians.



Daniel W. van der Weide (S'86–M'88) was born in Brookings, SD, in 1963. He received the B.S.E.E. degree from the University of Iowa, Iowa City, in 1987, and the M.S. and Ph.D. degrees in electrical engineering from Stanford University, Stanford, CA, in 1989 and 1993, respectively.

He held summer positions with Lawrence-Livermore National Laboratory and Hewlett-Packard, and full-time positions with Motorola as an Engineer and Watkins-Johnson Company as a Member of the Technical Staff. From 1993 to 1995, he worked as a post-doctoral researcher with the Max-Planck-Institut für Festkörperforschung (Solid State Research), Stuttgart, Germany, after which he joined the Department of Electrical & Computer Engineering, University of Delaware, Newark, as an Assistant Professor. He is now Associate Professor and Director of the Center for Nanomachined Surfaces.

Dr. van der Weide received the National Science Foundation CAREER and PECASE awards in 1997 and the Office of Naval Research Young Investigator Program award in 1998.