DISTRIBUTED BROADBAND FREQUENCY TRANSLATOR

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ABSTRACT

We present the first frequency translator based on a nonlinear transmission line (NLTL) phase shifter. Rather than excite shock waves on the NLTL in large signal mode, we use its voltage-variable delay to modulate the phase of a 0.5-3.0 GHz microwave signal, incorporating both amplitude and phase linearization. This enables coherent heterodyning with 42 dBc carrier and spurious suppression. The technique has significant applications in both instrumentation and sensing.

INTRODUCTION

Frequency 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], sampling receivers, and electronic terahertz systems[4].

Here we demonstrate the first frequency translator based on the nonlinear transmission line (NLTL) used as a phase modulator[5, 6] rather than in its customary role as a pico- and subpicosecond pulse generator[7]. Using both serrodyne (sawtooth) and triangle-wave modulation, we report coherent down-conversion of GHz signals to baseband at arbitrary rates set by the modulation frequency. This work indicates that single-chip, low-cost coherent microwave measurement systems can be realized.

BACKGROUND

Synchronous microwave measurements can be made using a variety of techniques, including optoelectronic "pump-probe"[8, 9] and electronic mixing with phase-locked synthesizers[4] as well as subharmonic sampling as employed in commercial microwave instruments. None of these methods, however, has been monolithically integrated as a system.

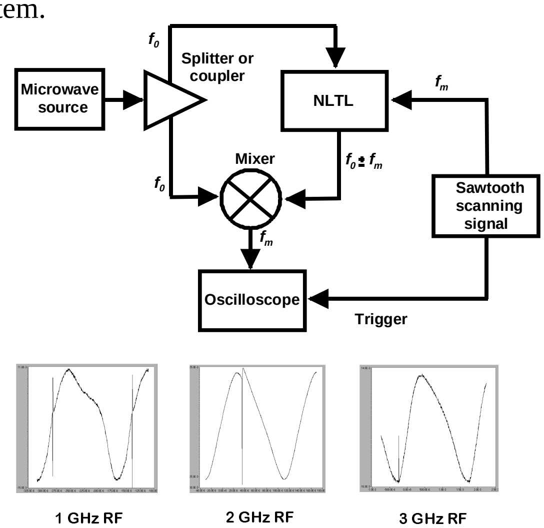

Figure 1. NLTL phase scanner system and baseband output without compensation. Phase shifter is serrodyne modulated at f_m and output of mixer has a fundamental at f_m. Note flyback transients.

Nonlinear transmission lines, by contrast, have been realized as integrated circuits, and 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[10].

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 a NLTL, enabling a complete single-chip coherent generation and measurement system, provided there is a source of coherent excitation signals.

PHASE SCANNING WITH NLTL'S

It would therefore be advantageous to integrate a means of coherent signal generation with the pulse and sampling circuits enabled by NLTL's. Here we propose and demonstrate a technique (Fig. 1) for eventual monolithic conversion of microwave signals to baseband, using a broadband distributed phase shifter modulated by either a sawtooth or triangle wave, predistorted for linearity and compensated for variations in amplitude with phase.

An ideal frequency translator should change the original frequency f_o of a signal V_i by some modulation frequency f_m by applying a phase $\theta = 2\pi f_m t$ that varies linearly with time, giving an output $V_o = \sin(2\pi f_o t + 2\pi f_m t) = \sin 2\pi(f_o + f_m)t$. This function can be realized in a continuous fashion using a rotary phase shifter driven at a constant rate such that $\partial\theta/\partial t = f_m$ [11].

As shown in Fig. 1, 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 shown 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. In particular, monolithic continuous, or analog, phase shifters are usually realized by integrating hybrid couplers with variable capacitances or gains arising from diodes or transistors. The couplers produce in-phase and quadrature components of the input which 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 essentially single-frequency (24 GHz) operation, full 360° serrodyne frequency translators have been realized in monolithic form[16].

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

While the use of the NLTL structure as a phase modulator was recognized early on[5], and has surfaced more recently in the literature[6, 18], it has only been in the context of phase shifting, and not frequency translation, as we propose here.

EXPERIMENTAL RESULTS

To demonstrate this principle, we built a scale model NLTL phase shifter on a brass block. The circuit consists of 30 abrupt junction diodes (C_{j0}=2pF) with 4.6 mm interval spacing for the first section and 20 abrupt junction diodes (C_{j0}=0.8pF) with 0.6 mm spacing for the second. Measurements of phase delay and transmission loss compared well with models done in both PSPICE and Libra.

As shown in Fig. 1, we first built a simple system with no compensation to demonstrate the principle of serrodyne modulation[13] with this structure. Although the circuit works as anticipated when modulated at f_m through 2π radians at the fundamental microwave frequency f_o, distortion in the output waveform, as well as the retrace (flyback) transient, is apparent.

We then made comprehensive measurements of the magnitude and phase of the NLTL transmission coefficient vs. bias and frequency, as shown in Fig. 2. With this data in look-up tables, we implemented the phase linearization and amplitude compensation scheme shown in Fig. 3. 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. 1), 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. 4).

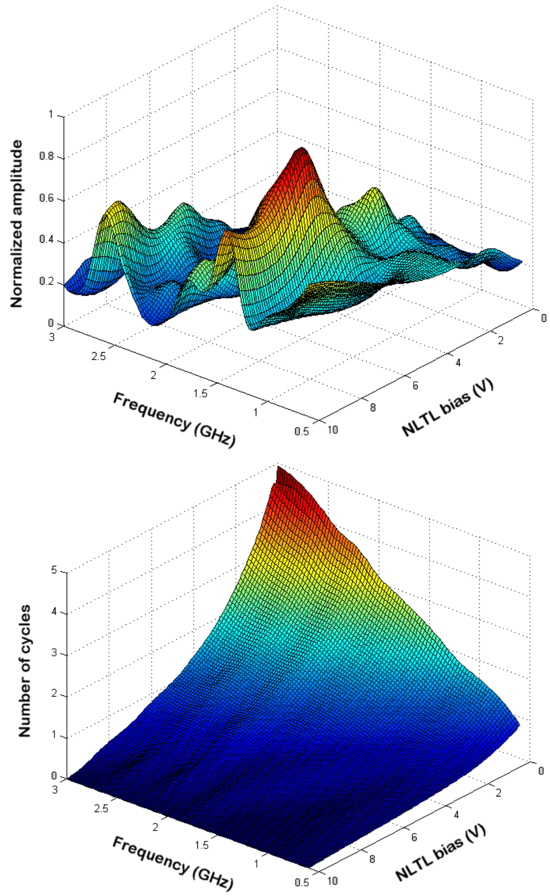

Figure 2. Amplitude (above) and phase (below) variation of NLTL transmission coefficient over bias and frequency.

In spite of the cleaner time-domain appearance of the triangle-wave modulated output, the serrodyne version exhibited >42 dB of spurious and harmonic suppression (Fig. 5), compared to 35 dB for the triangle wave. We can address this shortfall of the triangle wave modulation with more careful waveform reconstruction.

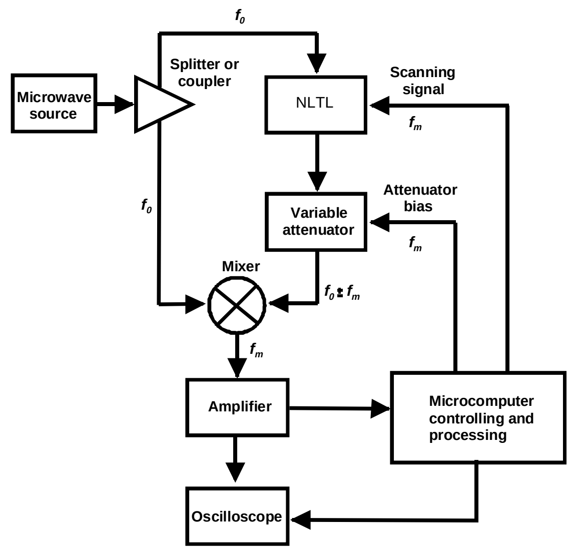

Figure 3. Compensated phase scanner for frequency translation.

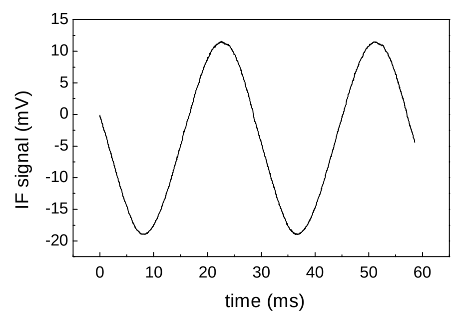

Figure 4. Beat note of 1.0 GHz signal at 35 Hz scan rate, triangle modulated.

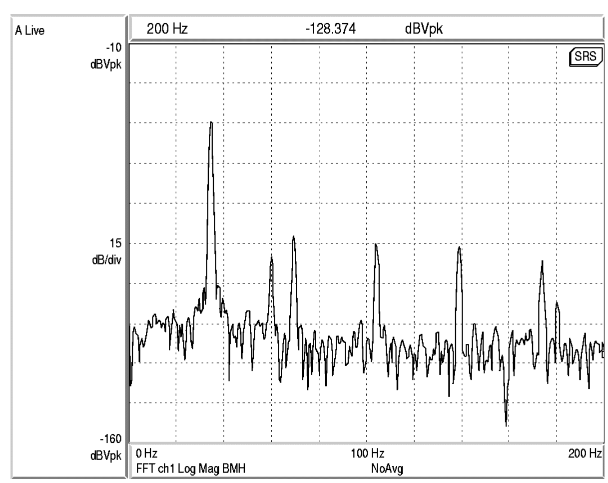

Figure 5. Fourier transform of sawtooth-modulated 1.0 GHz signal at 35 Hz rate (note spurious due to 60 Hz power line).

CONCLUSION

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 wideband micro- and millimeter-wave network analyzer system. This foundation can be extended to other specialized instruments, such as handheld reflectometers operating in the THz regime for applications such as demining and sensing gasses, nonmetallic weapons and explosives.

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