Heterodyne Technique Using Phase Shifter for RF and Microwave Measurement

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Abstract

This research paper proposes a technique for RF and microwave measurement of circuit and device characteristics using a heterodyne with a new phase (frequency) shifter. A nonlinear transmission line (NLTL) was employed as a main structure of the phase shifter in this work. A microwave reflectometer (one-port network analyzer) was then designed and constructed using the proposed heterodyne system. A microcomputer was utilized to control the instrument and devices, and process data. The results of measured reflection coefficients for 25 and 50 Ω loads using the proposed system agree very well with ones from a current commercial network analyzer. This technique may be extended to a two-port network analyzer and other higher frequency measurement systems.

Keywords : Heterodyne technique, phase shifter, microwave measurement, reflectometer.

1. Introduction

In high frequency measurement systems, two synthesizer sources are required to generate a heterodyne output signal for characterizing a device under test (DUT). Commercial vector network analyzers (VNAs) rely on only one synthesized source and use a sampling detector, rather than using two sources and a mixer, thereby trading dynamic range for lower cost. VNAs are very accurate and can now measure network parameters for up to 100 GHz. These measurement systems are bulky, expensive, and provide only narrow instantaneous bandwidths, so their use is limited to the laboratory and to linear devices and systems. Short-pulse lasers have been proposed [1,2] and pursued by several groups using a wide variety of methods to test ultrafast or wideband devices and circuits in the time domain, but laser-based approaches will not likely become portable, low-power, low-cost solutions for measuring 1-100 GHz signals.

A new solution proposed here can generate a heterodyne signal using only one microwave synthesizer with a phase (frequency) shifter to characterize DUT, as displayed in a schematic diagram of Fig.1. This technique can enable a complete, possibly monolithic, integration of wideband network analyzers, directly addressing the need for instruments to characterize devices, circuits, and systems, as well as the growing opportunities for sensors in this regime. Driving a phase shifter with serrodyne (sawtooth) modulation results in frequency shifting that can be used with an inexpensive (ultimately integrated) microwave source to coherently convert a wideband microwave signal directly to baseband. This invention, coupled with improved directional sampling circuits [3], could enable high-performance, inexpensive, and field-capable 100 GHz vector network analysis. In addition, several other new military and commercial applications such as terahertz reflectometers which would benefit from a monolithic coherent generation/detection system [4]. This approach is the first to present a clear path to complete integration of a coherent micro- and millimeter-wave measurement system.

2. Analysis and design

2.1 *NLTL phase (frequency) shifter*

Electronic phase shifters can be categorized into digital and analog phase shifters. Digital phase shifters generally use switches to alter the electrical phase length, while analog phase shifters vary a device reactance continuously to control the phase change. All electronic phase shifters using both passive and active components (*i.e.* PIN diodes and FETs) are generally employed as RF and microwave frequency shifting in the present day. Analog phase shifters can provide high resolution for small amount of phase change, whereas digital phase shifters are appropriate when a large step phase change is required. These phase shifters provide low resolution of step-phases causing low carrier and spurious sideband suppressions when operating as frequency shifters [5,6]. Many researchers, therefore,

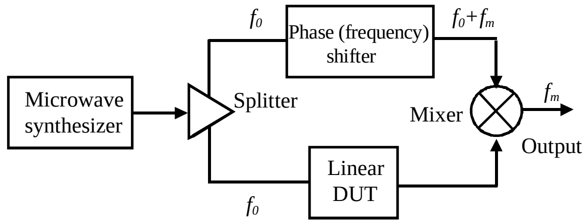

Fig. 1. Heterodyne technique using a phase (frequency) shifter to characterize a linear DUT.

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have developed some techniques to improve the characteristics of electronic frequency shifters by means of combination of analog and digital phase shifter circuits. Andricos *et al.* [7] proposed a new electronic frequency shifter by mixing a 6-bit digital phase shifter (combining the loaded-line and reflective types) with an analog phase shifting circuit to provide accurate tuning of phase from 0 to 360^{o}, however, their complicated frequency shifter circuit works only over a narrow frequency band and exhibits very high insertion loss.

A new phase shifter with a nonlinear transmission line (NLTL) structure has been proposed (Fig.2). An NLTL is a high impedance transmission line periodically shunted by reverse biased varactor diodes to produce a synthetic structure on which the small signal propagation velocity depends on the voltage-variable capacitance. For a large signal wave, the dependence of phase velocity or delay on the voltage of the traveling wave leads to wave compression and shock wave formation because a wave travels slowly at voltage levels near zero but quickly at reverse-bias voltages, where the depletion depth of the diode is large. However, when a small-signal signal propagates through an NLTL, the wave compression or shock wave formation is not significant because the voltage differences of the traveling wave are too small for it to modulate its own phase velocity [8]. Therefore, an NLTL can be useful as a small-signal device in the microwave phase shifting by applying an appropriate bias voltage for a certain phase. This phase shifter has broadband operation and low losses because its structure is distributed and low-Q. Therefore, the NLTL phase (frequency) shifter will be used in the proposed heterodyne system for RF and microwave measurement.

In this work, an NLTL with a series of 30 chip varactor diodes (R_s = 1.6 Ω and C_{jo} = 2.0 pF) was optimally designed using EEsof, a microwave circuit simulator. The chip varactor diodes were placed on a brass block and bond wire transmission lines with 300 Ω characteristic impedance were employed for connecting each diode (0.185 inch interval spacing). A bias tee consisting of blocking capacitors and a toroid RFC was put at the input for biasing of phase control voltage and chip blocking capacitors were also added at the output of the NLTL. The completed NLTL phase shifter is shown in Fig.3. The proposed phase shifter was then tested for shifting a frequency, verifying the phase changes from 0 to 360^{o} when continuously driving with the compensated sawtooth reverse bias voltage at a frequency of ~ 100 Hz generated from a microcomputer via a D/A board. The downconverted voltage output from the mixer is depicted in Fig.4. The carrier and sideband suppression of the phase/frequency shifter was consequently measured to be > 45 dBc. This confirms that the shifted signal is a nearly pure sinusoidal waveform suitable for high performance heterodyne systems. This NLTL phase/frequency shifter can be operated at operating frequency up to ~7 GHz.

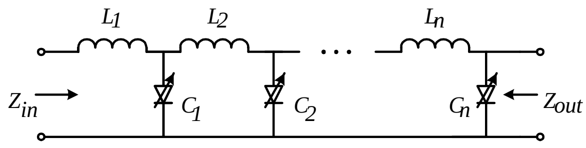

Fig. 2. A schematic of NLTL phase shifter.

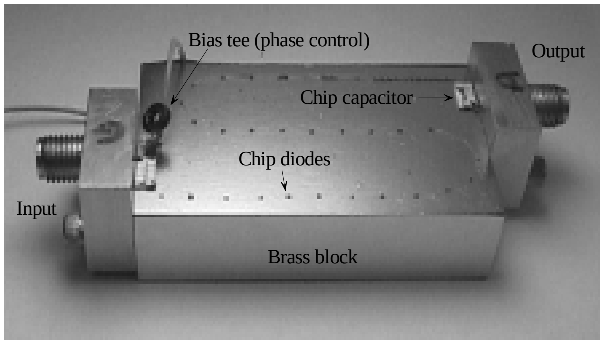

Fig.3. The constructed NLTL phase shifter consisting of 30 chip varactor diodes.

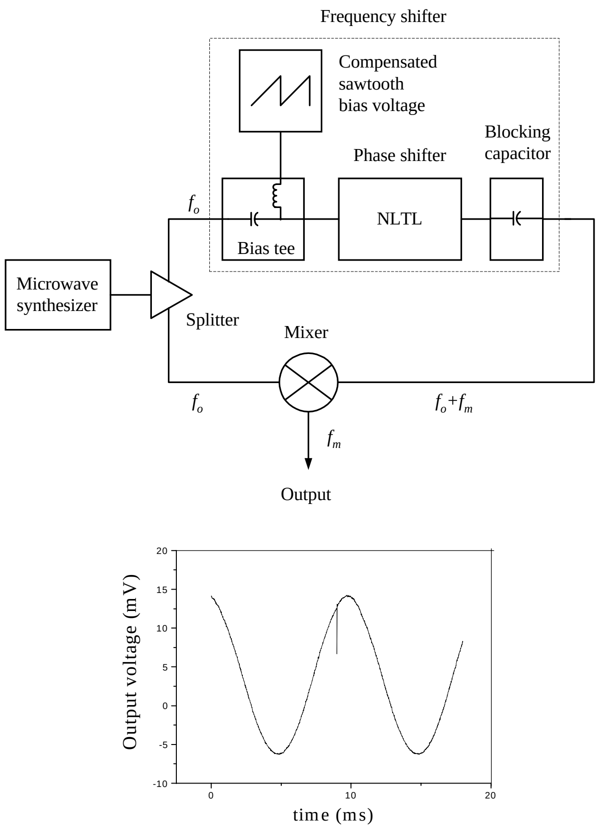

Fig.4. Set up for frequency shifting measurement (1 GHz RF and ~100 Hz offset) and the downconverted output waveform.

2.2 ***Heterodyne system***

A conventional microwave reflectometer consists mainly of a microwave synthesizer, a dual directional coupler and detectors. The ratio of the reflected wave and incident wave is the voltage reflection coefficient of the 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 [9]. Using standard loads to calibrate a conventional reflectometer has been proposed by Hollway and Somlo [10]. 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 developed into a six-port reflectometer (requiring four detectors) by Engen [11].

Meanwhile, 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, while not commercially available, 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.

The proposed reflectometer (one-port network analyzer) and its simplified signal flow graph are shown in Figs. 5(a) and (b). If the microwave synthesizer is matched, $\Gamma_S = 0$, and if the dual directional coupler is symmetrical, $S_{31} = S_{42}$ and $S_{32} = S_{41}$. Solving the signal flow graph will provide the ratio of P_{ref} and P_{inc}, as shown in the following equation

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

Three commercial 3.5 mm coaxial standards (matched, short and open loads) were used to calibrate the proposed reflectometer. From the above equation, substituting $P = P_M$ for matched load ($\Gamma_L = 0$), $P = P_S$ for a short circuit (Γ_L = -1), $P = P_O$ for an open circuit (Γ_L = 1), and $P = P_L$ for an arbitrary load or DUT, and solving the equation for these conditions yield the measured reflection coefficient as

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

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.

3. Experiment of heterodyne reflectometer

The NLTL phase shifter was utilized as a frequency shifter in the proposed heterodyne reflectometer system (Fig. 6). The signal from the microwave synthesizer was split into the frequency shifter input and mixer LOs. A dual-directional coupler (HP 11692D) was used to couple the incoming signal from the frequency shifter and the reflected signal from a DUT. These signals were fed into mixers (RF), resulting in downconverted ~100 Hz intermediate frequency (IF). The spectrum of the IF signals (20 periods) were taken by fast Fourior transform (FFT) using a LabVIEW® program on the microcomputer, from which the amplitude and phase of the incident (channel 1) and reflected (channel 2) waves were obtained. The calculation of complex reflection coefficient was then performed by the microcomputer. The measurement of 25 and 50 Ω loads from 1 to 3 GHz by using the calibrated reflectometer are shown in Figs.7 and 8, respectively. These results agree very well with ones from a commercial vector network analyzer (HP 8720D).

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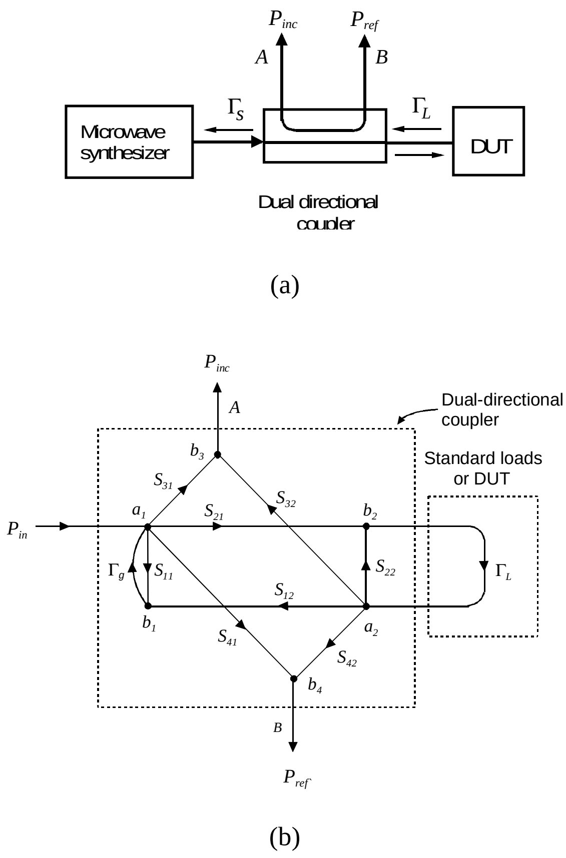

Fig. 5. The proposed reflectometer (a) schematic and (b) its simplified signal flow graph.

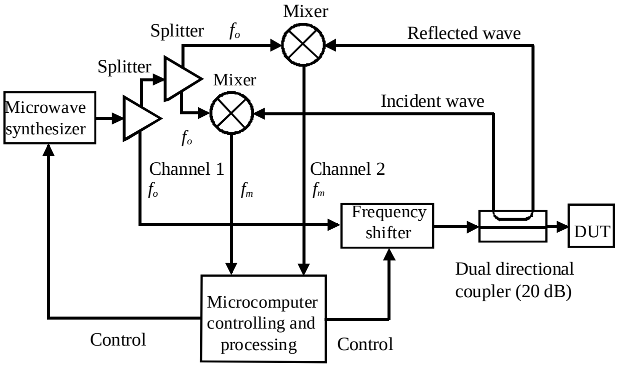

Fig. 6. The proposed heterodyne reflectometer system.

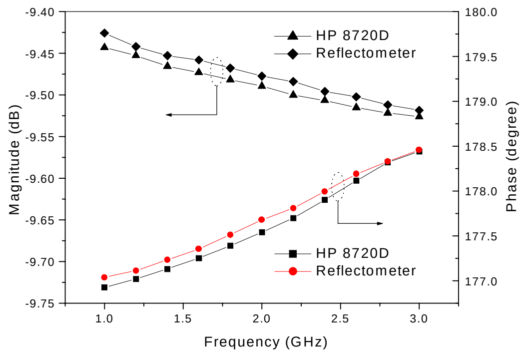

Fig. 7. Measurement of reflection coefficient for a 25 Ω load.

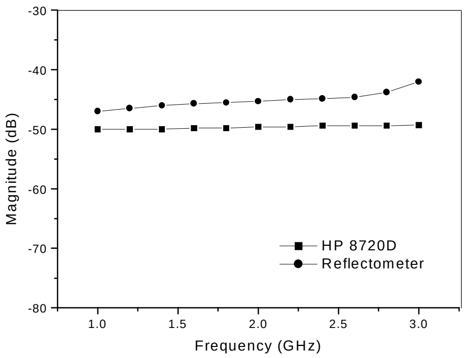

Fig. 8. Measurement of reflection coefficient for a 50 Ω load.

4. Conclusions

Using a NLTL phase/frequency shifter and the heterodyne technique for microwave measurement has been proofed to be a very high accuracy, high stability and potentially low-cost system. This new approach is expected to strongly support the future RF and microwave measurement systems because it offers a clear path toward complete integration into microwave integrated circuits (MICs). It will also have significant applications in other advanced high frequency instrumentation and sensor such as a terahertz reflectometer and gas detection systems.

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