A Broad-Band Impedance Indicator Employing a Phase-Shift Keying Modulator

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***Abstract*—A novel homodyne scheme for implementing a broad-band impedance indicator is proposed. It features a simple form made possible by using a modified quarternary phase-shift keying as a subcarrier modulation method. This method allows both the amplitude and the phase of a signal to be detected simultaneously by one single-ended mixer. A prototype indicator has assured the swept-frequency measurement over the band ranging from 8.6 to 10.4 GHz with the amplitude and phase errors of less than 5 percent and 5°, respectively. The capabilities are demonstrated by presenting examples of measurement.**

I. Introduction

With the development of advanced microwave devices and components, a microwave impedance indicator is becoming more and more necessary for their characterization. Whilet many forms of the indicator have been proposed [1]–[7], common to them all is the problem of how to detect both the amplitude and the phase of a signal simultaneously. In a conventional indicator [4]–[11], this is accomplished by detecting separately the real and imaginary components of a signal normalized to a reference phase, made possible by incorporating two homodyne systems into the indicator. Such a scheme is valid for fixed-frequency measurement, but two problems are involved in broad banding [6]–[8]: two balanced mixers in two homodyne systems need to be a matched pair with a flat frequency response, and the signal and reference channels of two homodyne systems should have an identical phase-versus-frequency slope. Although the latter problem can be solved by equalizing the electrical path lengths of both channels, it requires an elaborate arrangement of microwave components. It is thus expected to alleviate the broadbanding problem if one homodyne system should be available for detecting both the real and imaginary components.

A frequency-division multiplexing is well known as a valid technique for transmitting several messages on one transmission facility. This technique is applied to an impedance indicator to solve the problem of one homodyne system for the two components. The key to multiplexing is the adoption of a modified quarternary phase-shift keying (PSK) as a subcarrier modulation method. This modulation method also makes it possible to replace a balanced mixer by a single-ended mixer, thus leading to simplification of the indicator.

This paper describes the principles of operation and the accuracy in a swept-frequency measurement. The principles are experimentally confirmed by the performance of a prototype indicator developed for measurement of X-band components. Its details and capabilities are also described.

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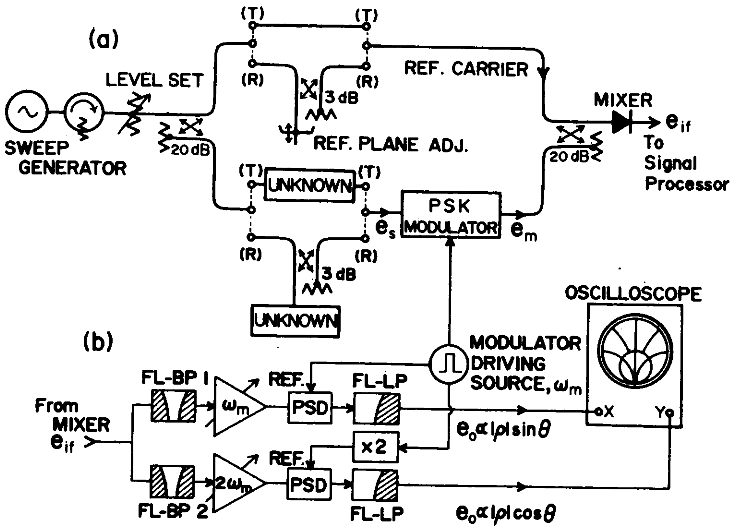

Fig. 1. A broad-band impedance indicator. (a) Microwave setup for (*T*) transmission and (*R*) reflection coefficient measurement, and (b) circuit configuration of the signal processor.

II. Principles of Operation

Fig. 1 shows the configuration of the impedance indicator. It consists of two main parts: a microwave homodyne system and a low-frequency signal processor. It is understood in the following paragraphs that the output of a sweep generator is levelled and all microwave components are of matched broad-band type with a flat frequency response.

The two paths connecting two directional couplers form the signal and reference channels of the homodyne system. An arrangement denoted by (*T*) measures a transmission coefficient, and that by (*R*) a reflection coefficient. In either arrangement the two channels should have an identical electrical path length. This is easily made because of the fewer components and the symmetry in the configuration of the two channels. The PSK modulator and a mixer operate as a subcarrier modulator and a coherent detector, respectively, in a frequency-division multiplexing system.

The signal processing necessary for multiplexing is to divide a signal into two components in quadrature and then to allot a separate band for each component. Recalling that a phase modulation produces sideband pairs in quadrature and that they have different angular velocities in a phasor diagram, one recognizes a phase modulation to be a proper method for the multiplexing process. A digital phase modulation is superior in broadband operation to an analog one [12]; quantizing an analog phase-shift using three discrete levels, one obtains the modified quarternary PSK used here, which develops 0°, −90°, 0°, and 90° of phase shift in every quarter period of modulation frequency.

The detection process can be explained by expanding the modulated signal into a Fourier series and representing the resultant sidebands on a phasor diagram. The signal from the unknown is written to be of the form

$$e_s = \mathrm{Re}\{\rho V_s \exp(j\omega t)\} = |\rho| V_s \cos(\omega t + \theta) \quad (1)$$

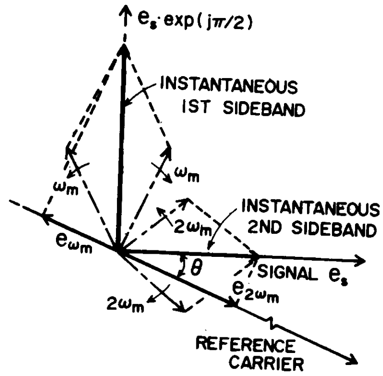

Fig. 2. The phasor diagram of the signal, first and second sidebands, and reference carrier. The IF signal is the projection of the instantaneous first and second sideband vectors along the reference carrier vector.

where $\rho = |\rho| \exp(j\theta)$ is a reflection or transmission coefficient being measured. The modulated signal is given by, assuming the PSK modulator is lossless,

$$e_m = |\rho| V_s \cos(\omega t + \theta + \phi) \quad (2)$$

where ϕ denotes the phase shift due to the PSK modulator. For the present modified quarternary PSK, it is written as

$$\phi = (j)^{n+1}\{1 + (-1)^{n+1}\}(\pi/4) \quad (3)$$

for

$$n\pi/2 \le \omega_m t \le (n+1)\pi/2, \quad (n = 0,1,2,3)$$

where ω_m is the modulation angular frequency. Expanding (2) into a Fourier series, one has:

$$\begin{aligned} e_m = & \sum_{\nu=0}^{\infty} (-1)^{\nu(\nu-1)/2} \frac{\sqrt{2}|\rho| V_s}{(2\nu+1)\pi} \\ & \cdot [\sin\{\omega t + (2\nu+1)\omega_m t + \theta\} \\ & + \sin\{\omega t - (2\nu+1)\omega_m t + \theta\}] \\ & + \sum_{\nu=0}^{\infty} (-1)^{\nu-1} \frac{|\rho| V_s}{(2\nu+1)\pi} [\cos\{\omega t + 2(2\nu+1)\omega_m t + \theta\} \\ & + \cos\{\omega t - 2(2\nu+1)\omega_m t + \theta\}] \end{aligned} \quad (4)$$

The modulated signal consists of an infinite number of sidebands. Attending only to the first and second sidebands, one obtains the phasor representation shown in Fig. 2. The signal is represented as a fixed-reference vector by reducing the whole angular velocity of vector by the signal angular frequency ω. This stationary phasor diagram shows explicitly that the signal is just partitioned as is required for multiplexing. The amplitude of the second sideband, in-phase component, is 3 dB smaller than that of the first sideband, quadrature component. This unbalance in partition ratio is balanced or compensated for by adjusting the gains in IF stages.

Fig. 2 also includes the reference carrier incident upon the mixer, which is a stationary vector making an angle θ with respect to the signal vector. Assuming low-level mixihg and linear-law detection, one obtain the IF output as the projection of the instantaneous sideband vectors along the reference carrier axis. Thus

$$e_{IF} = e_{\omega_m} + e_{2\omega_m} = k|\rho|V_s\{\sqrt{2}\ \sin\theta \cos\omega_m t + \cos\theta\ \cos 2\omega_m t\} \quad (5)$$

where k is a constant associated with a modulation loss of the PSK modulator and a conversion loss of the mixer.

The IF output is applied to the signal processor shown in Fig. 1(b), where it is separated into e_{ω_m} and $e_{2\omega_m}$ components by means of bandpass filters (FL–BP's). After amplified, each component is mixed with the IF reference of the same frequency in a linear-law phase-sensitive detector (PSD) to produce a video signal. The output of PSD contains, besides the video signal, the residual IF reference, but it is filtered out by a low-pass filter (FL–LP). The dual channel process provides the video signals proportional to $|\rho| \sin\theta$ and $|\rho| \cos\theta$. Applying them to the horizontal and vertical axes of an X-Y oscilloscope, one obtains a polar representation of a reflection or transmission coefficient on a CRT overlay.

The calibration procedure is: first, the component of well-known property, say, a short in (R) connection or an empty waveguide in (T) connection, is connected in place of an unknown. Next, the gains of two IF amplifiers are adjusted while viewing an oscilloscope display until it indicates the proper value.

III. Accuracy of Measurement

The accuracy in amplitude and phase measurement depends on whether a fixed- or swept-frequency measurement is involved. In a fixed-frequency measurement, excellent accuracy is obtainable, for the calibration procedure nullifies the error that would otherwise be caused by mismatches of microwave components, and the IF detection insures the drift-free measurement. In a swept-frequency measurement, however, the mismatches cannot be completely tuned out, thus causing a systematic error.

There are four components whose mismatches contribute to the systematic error: two directional couplers, mixer, and PSK modulator. While the precise evaluation requires a flowgraph analysis, the systematic error is given, in a first order approximation, by adding each individual contributions. The contributions of the mismatched directional couplers and mixer have been already discussed in [6]–[8], [13]. The error source inherent in the present indicator is the mismatch of the PSK modulator. It can be described by two factors: the amplitude unbalance and the phase-shift deviation [14].

The amplitude unbalance causes an unexpected amplitude modulation. Let the signal amplitude when $\phi = 0°$, $-90°$, and $90°$ be 1, $1 - \epsilon_-$, and $1 - \epsilon_+$, respectively. Expanding the modulated signal into a Fourier series under this unbalance tells that the amplitude of the quadrature component decreases from the proper value by an amount of $(\epsilon_- + \epsilon_+)/2$ while the in-phase component remains invariant. Thus the fractional error in amplitude measurement becomes maximum when $\theta = (2n + 1)\pi/2$, and the phase error becomes maximum when $\theta = (2n + 1)\pi/4$. Table I summarizes the amplitude and phase errors due to the amplitude unbalance.

TABLE I

The Amplitude and Phase Errors Due to the Amplitude Unbalance, $\epsilon_- + \epsilon_+$, of the PSK Modulator

Error \ θ	$n\pi$	$(2n+1)\pi/4$	$(2n+1)\pi/2$
$\frac{\Delta\lvert\rho\rvert}{\lvert\rho\rvert}$	0	$\frac{\epsilon_-+\epsilon_+}{4}$	$\frac{\epsilon_-+\epsilon_+}{2}$
$\Delta\theta$	0	$\tan^{-1}\frac{\epsilon_-+\epsilon_+}{4}$	0

TABLE II

The Amplitude and Phase Errors Due to the Phase-Shift Deviation, δ, of the PSK Modulator

Error \ θ	$n\pi$	$(2n+1)\pi/4$	$(2n+1)\pi/2$
$\Delta\lvert\rho\rvert/\lvert\rho\rvert$	$\delta^2/2$	$\delta/2$	δ^2
$\Delta\theta$	$\tan^{-1}\delta$	$\tan^{-1}(\delta/2)$	0

The phase-shift deviation, the deviation in phase shift from ±90°, causes the crosstalk between the in-phase and quadrature components; the first sideband contains, besides the quadrature component, the in-phase component. Let the deviation be δ rad. Then, due to the crosstalk, the instantaneous first sideband vector inclines by δ from the proper position shown in Fig. 2, with the consequence that the video signal to a horizontal axis is proportional not to $\sin\theta$ but to $\sin(\theta + \delta)$. The phase error thus becomes maximum when $\theta = n\pi$, and the fractional amplitude error becomes maximum when θ nearly equals $(2n + 1)\pi/4$. Table II summarizes the amplitude and phase errors due to the phase-shift deviation.

IV. Details of Prototype Indicator

The impedance indicator based upon the principles described above has been implemented for measurement of X-band components. The phase shifter using latching ferrites has been employed to form the PSK modulator. It consists of two bits of ferrite toroid of rectangular shape placed longitudinally in the center of an X-band waveguide. The current pulse of bipolar return to zero is fed to a wire threaded through each ferrite toroid to magnetize it alternately to two remanences. The differential phase shift of each bit is 90°. Fig. 3(a) shows the phase shift due to the first bit. The second bit is triggered after a delay of a quarter period, so that the phase shift becomes as shown in Fig. 3(b). Fig. 3(c), the sum of (a) and (b), provides the modified quarternary PSK. The modulation frequency is 50 kHz.

The amplitude unbalance, $\epsilon_- + \epsilon_+$, and the phase-shift deviation, δ, of the PSK modulator have been measured by the procedure described in [14]. They are below 0.056

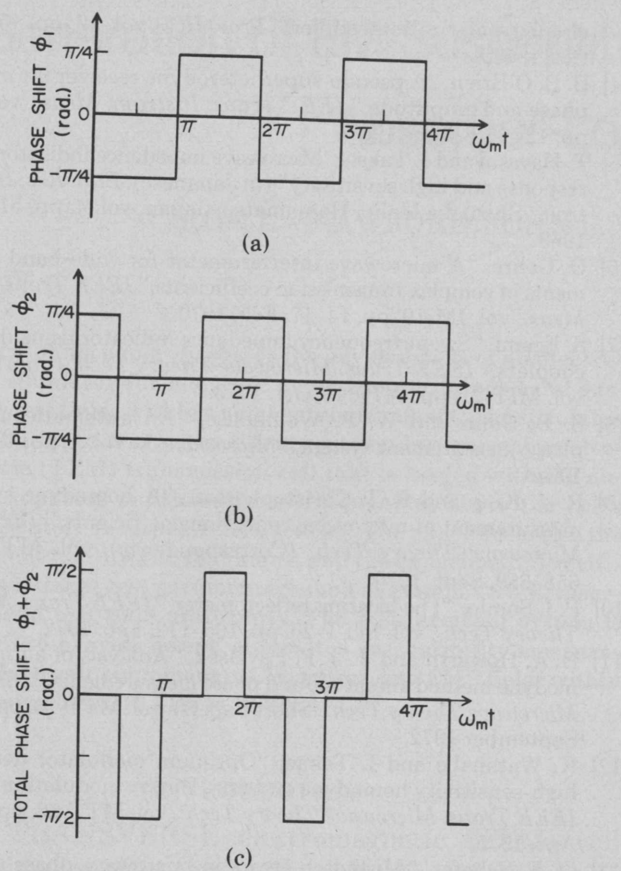

Fig. 3. (a) The phase shift of a microwave signal when passed through the latching ferrite phase shifter with the differential phase shift of 90°, (b) that lagged by a quarter period from (a), and (c) the sum of (a) and (b): the modified quarternary PSK.

and 0.087 rad, respectively, over the frequency band from 8.6 to 10.4 GHz. These two factors dominate the accuracy and the bandwidth of the present indicator. Referring to Tables I and II, the amplitude and phase errors in this frequency range are estimated to be less than 5 percent and 5°, respectively, for all values of θ.

All microwave components other than the PSK modulator are commercially available. Specifically, the bifurcated couplers have been used to facilitate a symmetrical arrangement of the two channels. Although not shown in Fig. 1(a), an isolator has been inserted in front of the mixer to avoid multiple reflection due to the mismatch of the mixer and unexpected discontinuity in waveguide junctions.

The minimum detectable signal power is −114 dBm. The reference carrier power is 3 dBm. Since the mixer assures a linear-law detection up to −7 dBm in signal power, the dynamic range as high as 107 dB is obtainable.

FL-BP 1 and 2 in the signal processor consist of three stage Chebyshev filters, having pass-bands from 30 to 70 kHz and from 80 to 120 kHz, respectively. The 10 kHz bandwidth from 70 to 80 kHz forms a guard band to avoid the crosstalk between the fundamental and second harmonic IF components. The two FL-LP's have identical configuration and consist of three stage Chebyshev filters. The cutoff frequency is 20 kHz, which limits the response speed of the indicator.

Fig. 4 shows three examples of measurement. Fig. 4(a), an example of fixed-frequency measurement, shows an impedance locus of a P-I-N diode when its bias voltage is swept. Figs. 4(b) and (c), examples of swept-frequency measurement, show an admittance locus of a single-ended cavity and a transmission coefficient of a transmission cavity around resonance, respectively.

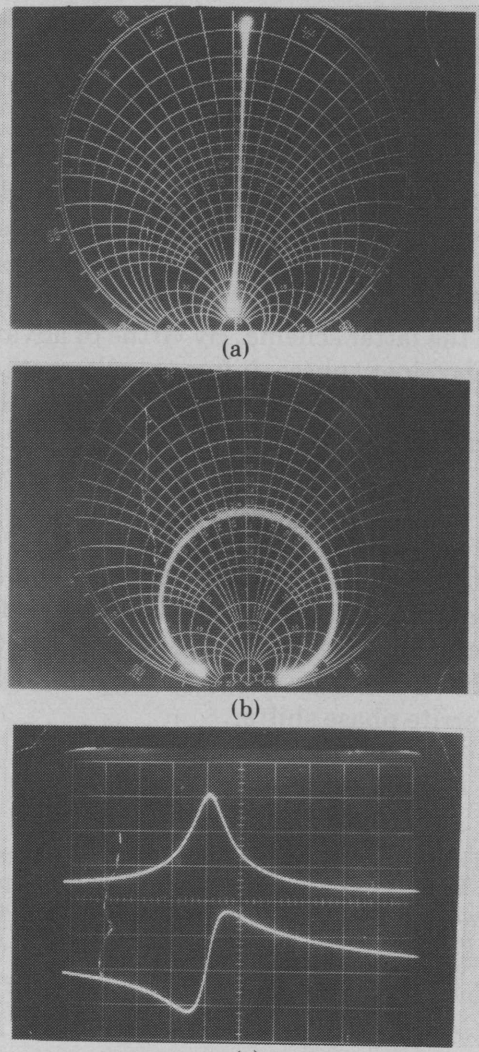

Fig 4. (a) An impedance locus of a P-I-N diode. The bias is swept from −5V to 0.9V at repetition frequency of 60 Hz. Diode: V958 (NEC) in a reduced height mount. Frequency of measurement: 9.5 GHz. (b) An admittance locus of a TE_{102} rectangular single-ended cavity. Swept frequency range: 9450 ± 10 MHz. (c) The real (upper trace) and imaginary (lower trace) parts of the transmission coefficient of a TE_{105} rectangular transmission cavity. Vertical scale: 0.2/div. Horizontal scale: 3 MHz/div.

V. Conclusions

One scheme of an impedance indicator is described which allows the swept-frequency measurement over a broad bandwidth. It takes a simple form made possible by applying a frequency-division multiplexing technique to simultaneous amplitude and phase detection. The key component to multiplexing is the PSK modulator. The practical design of the PSK modulator together with a prototype indicator developed for characterization of X-band components are also given.

Because of IF detection, sensitivity and the dynamic range are such as to be compared favorably with those of a conventional superheterodyne system; therefore, the detection scheme described herein is applicable to other instruments such as a near field antenna pattern measuring system, an ESR spectrometer, and thickness and moisture content measuring instruments in industrial applications.

The disadvantage is that it requires the PSK modulator to be somewhat sophisticated form. This would, however, be overcome by altering the detection scheme from the frequency-division to time-division multiplexing, for a binary 90° phase shifter will suffice for the multiplexing process in the latter scheme. By virtue of advanced technology of the binary phase shifter, this alternation will lead to extending the bandwidth of the indicator. The details is now under examination.

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