A New Precision Voltage Control Scheme for the Amplitude of Oscillators

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Abstract—**A simple technique for precisely controlling the amplitude of oscillators is described. The control parameter is a voltage and the relationship between this voltage and the amplitude of oscillation is linear. Two applications of the scheme, namely, in amplitude stabilization of oscillators and in generation of stabilized amplitude modulated signals, are discussed. Experimental results agree closely with the expected performances. The scheme is versatile and suitable for mass production.**

I. Introduction

SINUSOIDAL oscillators are required in many areas such as communications [1], instrumentation, measurements [2], etc. There are applications where stabilization of the amplitude of oscillation is vital, for example, in sweeping oscillators frequently used in spectrum analyzers [3]. It is desirable here that the amplitude of oscillations be substantially constant as the frequency is varied over a required range. In some situations, in addition to stabilization a control over the amplitude is also required, for example, in standard-signal generators [2]–[4]. Here the amplitude is controlled by a modulating signal while the carrier frequency is generated by the oscillator itself. The signal generator should maintain the modulation index at a constant value while the carrier is swept over a band of frequencies.

The purpose of this article is to present a simple new scheme for precision voltage control of oscillator amplitudes. In order to present the scheme, let us first review the principles behind the existing amplitude stabilization methods.

II. Review of Existing Amplitude Stabilization Methods

All the existing techniques can be recognized as belonging to one of two classes. The first of these classes uses what may be termed as a direct approach [5]–[7] where some sort of compensating circuitry is built into the oscillator which acts in such a way that the influence of the parameters affecting the amplitude is counteracted. The scheme under this approach can further be divided into two groups.

Fig. 1 shows a typical transfer characteristic of the amplifier used in one of these groups. The gain m_1 is

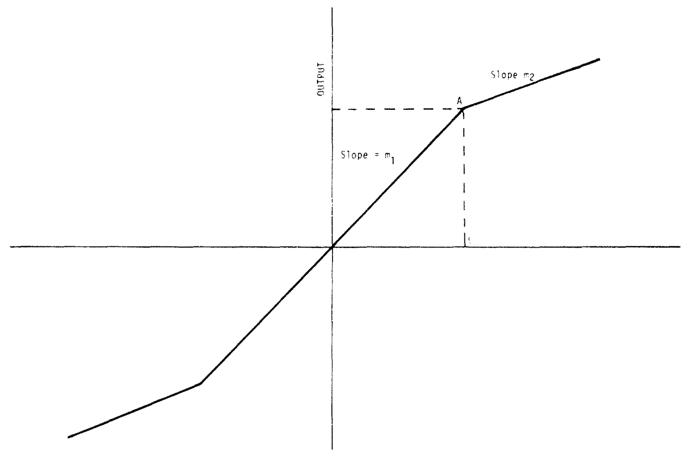

Fig. 1. Transfer characteristics of an amplifier. Gain m_1 helps grow the amplitude of oscillations while gain m_2 retards it.

designed to set the circuit to growing oscillations. Once the amplitude is such that the point A in the transfer characteristic is reached or exceeded, the gain is reduced to m_2 to retard any further growth in the amplitude. Equilibrium is achieved at a point slightly beyond A. Distortion is inevitable as the oscillations embrace two different regions in a single cycle. Break point A determines the amplitude of oscillations while the magnitude of distortion is determined by the gains m_1 and m_2. Zener diodes are commonly used in practice to realize the break point A.

Let k_c be the critical gain of the amplifier that is necessary for pure sinusoidal oscillations and let m_1 and m_2 be chosen such that $m_1 > k_c > m_2$. Under these conditions V_{mi}, the peak value of the amplitude of oscillation at the input of the amplifier will exceed δ experiencing two different gains in a single cycle. The ratio V_{mi}/δ will, then, be a measure of distortion. V_{mi}/δ will be unity for zero distortion and as V_{mi}/δ increases the distortion will also increase. By following the approach given in [7], we may show that the critical gain k_c is related to m_1, m_2, and V_{mi}/δ as

$$k_c = m_2 + \frac{2}{\pi}(m_1 - m_2) \cdot \left[\sin^{-1}\left(\frac{\delta}{V_{mi}}\right) + \left(\frac{\delta}{V_{mi}}\right)\sqrt{1 - \left(\frac{\delta}{V_{mi}}\right)^2}\right]. \quad (1)$$

Given m_1, m_2, and k_c we can solve the above equation for V_{mi}/δ which will be a measure of distortion at the output. A

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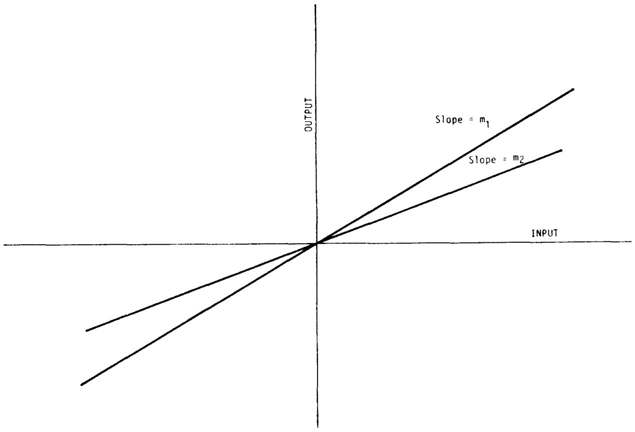

Fig. 2. Transfer characteristics of amplifiers with two different gains. Gain m_1 will help grow the oscillation while gain m_2 will help it to decay exponentially.

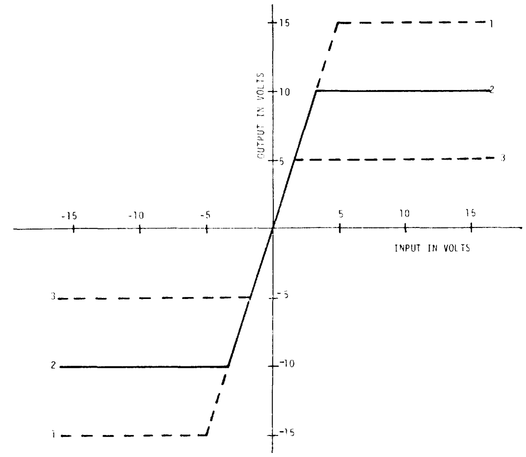

Fig. 3. Transfer characteristics of an amplifier of gain 3 using ML741 when the supply voltage is: 1) ± 15 V. 2) ± 10 V. 3) ± 5 V.

little reflection will show that for a given k_c and m_1, distortion will increase with increasing values of m_2. Similarly, an increase in m_1 will increase the distortion for given values of k_c and m_2.

The second group exploits the transient behavior of the oscillators. Initially the pair of poles are placed on the right half of the s-plane, close to the imaginary axis. As a result, the oscillation builds up exponentially. Once the amplitude reaches the desired level, the poles are quickly moved to the left so that oscillation starts decaying. Just as the amplitude goes below the desired level, the poles are pushed back to their original positions. This is usually accomplished by an automatic gain control arrangement, as illustrated by Fig. 2. Gain m_1 places the poles on the right-hand side of the s-plane while gain m_2 brings them to the left. In a practical circuit the gain varies continuously from m_1 to m_2 to enable the amplitude to be controlled closely.

As the gain is controlled automatically to stay close to a value just enough to sustain the oscillation, the distortion in the output is the least. The disadvantages with this method is that the details of the amplifier must be made accessible to the designer and that the entire design procedure needs to be repeated as one moves from one oscillator circuit to another. It also involves the use of nonlinear devices such as FET as a voltage-controlled resistor which may introduce distortion of its own.

In the other class of oscillators, amplitude stability is achieved by starting first with a circuit where stability is not a problem and then obtaining the desired wave shape and frequency range of oscillations by elaborate and complex circuitry [5]. Tektronix function generator TM 504/FG 501 and Hewlett-Packard spectrum analyzer 141T/8552A/8552B are good examples. In Tektronix function generator a triangular wave of constant amplitude is first generated followed by wave shaping circuits. The sinusoidal wave thus produced has very low change in amplitude for a frequency range of a decade or more. The Hewlett-Packard spectrum analyzer uses a voltage controlled oscillator that originally produces a frequency range from 46.85 to 47.15 MHz. By using the hetrodyne principle a frequency variation of 0 to 300 kHz with little change in amplitude is obtained.

In the proposed method, amplitude is regulated by controlling the dc power supply voltages applied to the amplifiers contained in the oscillator circuits.

III. Identification of the Control Parameter

In any sinusoidal oscillator circuit without additional stabilization circuitry, the amplitude of oscillations grows exponentially until it reaches a level beyond which some sort of circuit nonlinearity comes into effect. This, in turn, prevents any further growth in amplitude. At this point the amplitude is said to have reached a steady state. In practice it is usually the amplifier that introduces the nonlinearity. Fig. 3 shows the transfer characteristics of an amplifier of gain 3 using the operational amplifier ML741. This exhibits a linear relationship between the input and the output only over a certain dynamic range. Any increase in the input beyond this range brings about an abrupt saturation at the output. This saturation voltage is directly proportional to the power supply voltage. It is shown in Fig. 3 how the dynamic range can be altered simply by altering the power supply voltage. It should be noted that the dynamic range is linear with respect to the supply voltage since the saturation levels are equally spaced.

Comparing Fig. 1 and Fig. 3 we conclude that each of the amplifier characteristics of Fig. 3 corresponds to a case where $m_1 \geq k_c$ and $m_2 = 0$. Distortion can be made arbitrarily small by tuning m_1 to be as close as possible to k_c. Theoretically we can achieve zero distortion by making $m_1 = k_c$. If we make the assumption that the distortion is nearly zero then we have that V_{mi}/δ equals to 1. Hence if we vary δ then V_{mi} will also vary in the same direction to keep V_{mi}/δ equal to unity. The peak value of the signal V_{mo}, at the output is then given by

$$V_{mo} = K_c V_{mi} = K_c \delta. \qquad (2)$$

Thus a variation in δ will result in a corresponding variation in the amplitude of oscillation at the output. The important difference between Fig. 1 and Fig. 3 is that δ is fixed in the former while in the latter it is made variable with the use of a

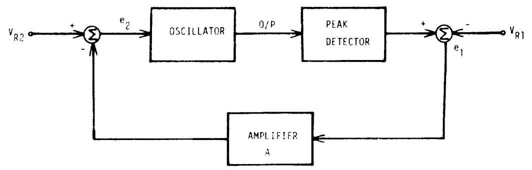

Fig. 4. Block schematic of amplitude stabilizer.

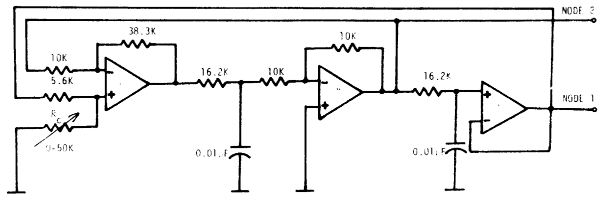

Fig. 5. A resistor controlled oscillator.

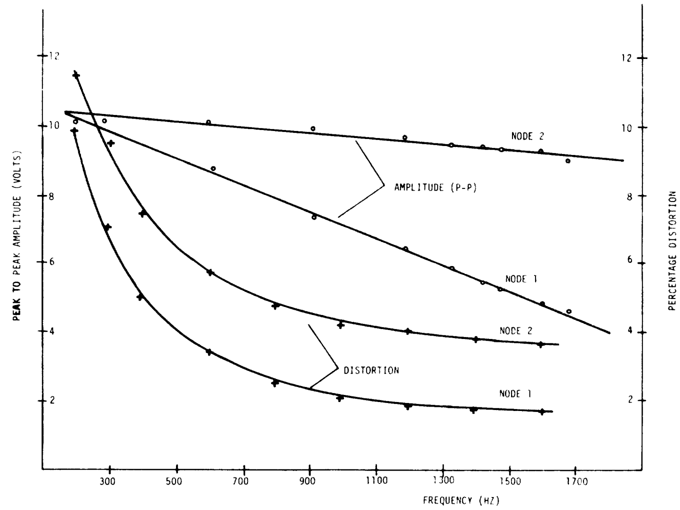

Fig. 6. Amplitude and distortion characteristics of oscillator in Fig. 5.

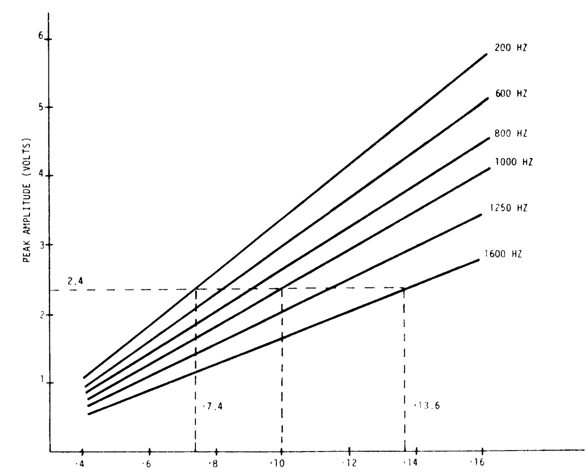

Fig. 7. Amplitude of oscillation as a function of power supply voltage.

variable power supply. It should be noted that the relationship between the amplitude of oscillation and the supply voltage is linear, as the dynamic range is linear with respect to the supply voltage.

IV. The New Scheme

The block schematic of the proposed amplitude control method is shown in Fig. 4. The output of the peak detector is compared with a reference voltage V_{R1}, which, as will be seen subsequently, determines the amplitude of oscillation. The error voltage e_1 is amplified and further compared with a second reference voltage V_{R2}. The error voltage e_2 determines the supply voltage to the oscillator.

It is observed from the block diagram that if the peak (amplitude) value increases, the error e_1 increases, which after amplification, decreases the supply voltage by controlling e_2. This, in turn, tends to decrease the amplitude of the oscillations. At equilibrium the amplitude of oscillations is close to V_{R1}. The value of V_{R2} is so selected as to supply the necessary supply voltage to the oscillator when e_1 is adjusted to zero. Clearly there is no control on the amplitude of oscillation if the gain A is zero. As the value of the gain A is increased, the variation of the amplitude of oscillation from V_{R1} is reduced. The larger the value of A the smaller is the value of this variation. Beyond a certain value any further increase in A results only in the amplification of the noise present in the circuit. The design of V_{R1}, V_{R2}, and A is illustrated in the following section by applying the technique to a specific oscillator. The degree to which a stable control over the amplitude of oscillation is obtained depends mainly on the extent to which V_{R1} and V_{R2} are kept stable. Any other variation in the circuit has relatively little effect on the amplitude. It is also clear that a stabilized amplitude modulation may be derived simply by modulating V_{R1}.

The above scheme is now used in two applications: (i) amplitude stabilization of an oscillator (ii) regulated amplitude modulation.

V. Amplitude Stabilization of Oscillators

It is clear from the discussion in the proceeding section that amplitude stabilization is achieved by simply controlling the peak value to remain close to a given reference voltage V_{R1}. To demonstrate how this can be done in practice, a recently reported tunable oscillator circuit [8] is considered. The circuit is reproduced in Fig. 5 for convenience. In this circuit the amplitude decreases as the frequency is increased. Signals tapped at two different nodes have distinct amplitude and distortion characteristics. They are shown in Fig. 6. It is seen that the output at node 1 has a lower distortion but a higher variation in amplitude as compared to node 2. The low-pass filtering that the signal at node 2 undergoes before appearing at node 1 accounts for the decrease in distortion.

Let us, therefore, assume that we are interested in tapping the output from node 1. Fig. 7 shows the relationship between the amplitude of oscillations and the supply voltage for different nominal frequencies. By supply voltage we mean the value of the positive and the negative supply voltage for the operational amplifier. The frequencies of oscillations were found to be affected negligibly by the supply voltage. For example the deviation in the frequency of oscillation is less than 1 percent for a nominal value of 1 kHz and for a 300-percent change in the supply voltage from

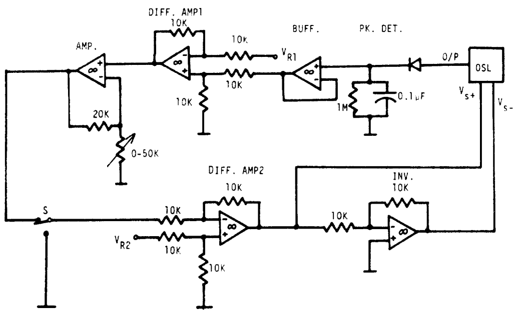

Fig. 8. The feedback scheme to stabilize the amplitude.

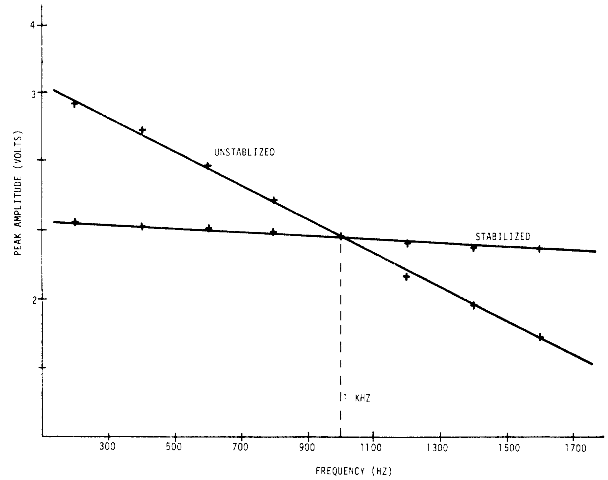

Fig. 9. Amplitude of oscillation before and after stabilization.

± 5 V to ± 15 V. If a better performance is desired then frequency stabilization of the oscillator is recommended [5]. We observe from Fig. 7 that if the amplitude of oscillations is to be kept, say, at 2.4 V peak at all frequencies, then the supply voltage has to be swept from ± 7.4 V at 200 Hz to ± 13.6 V at 1600 Hz.

Fig. 8 is a simple circuit realization of the block schematic of Fig. 4. The realization uses operational amplifiers. Proper values for V_{R1}, V_{R2}, and gain A can be selected by the following procedure sequentially. 1) Disconnect the feedback loop using switch S and adjust V_{R2} such that a ± 10-V power supply is applied to the oscillator. Ideally V_{R2} should be 10 V to get this. A slight adjustment of V_{R2} may be necessary to compensate for any imperfection in the components. 2) Tune the oscillator to 1 kHz by varying R_c (see Fig. 5). The frequency of 1 kHz is chosen because this is midway in the frequency range of interest, namely 200 Hz to 1600 Hz. At 1 kHz and for a supply voltage of ± 10 V, the oscillator should have an amplitude of 2.4 V as indicated by Fig. 7. The output of the peak detector will then be close to 2.4 V, the deviation being due to the imperfection of components. The RC time constant of the peak detector is a trade off between response time and ripple factor. 3) Adjust the reference voltage V_{R1} such that the error voltage e_1 is zero. If the peak detector were ideal, then V_{R1} will have to be 2.4 V to make e_1 zero. Adjustment of V_{R1} may be necessary to account for any imperfection in the peak detector. 4) Once V_{R1} and V_{R2} are adjusted, throw the switch S back to reconnect the feedback loop. Only the gain A remains to be adjusted next. The higher the gain A the better the stabilization. However, as mentioned before, beyond a certain value any further increase in A results in the amplification of noise present in the circuit, one obvious source being the ripple at the output of the peak detector. The optimum value of A, for the present case, has been found to be 20. The noise due to ripple can be reduced by replacing the peak detector by a full wave rectifier followed by a filter. The value of A in that case can be increased still further.

Fig. 9 shows the amplitude characteristics of the oscillator with and without stabilization. It is observed that the stabilization has reduced the amplitude variation from over 106 percent to less than 8 percent. The value of 10 V for V_{R2} has been chosen so that the supply voltage swings more or less equally on either side of ± 10 V, from ± 7.4 V to ± 13.6 V. Note also that the amplitude characteristics, with and without stabilization, cross over at 1 kHz, the frequency at which the system is aligned.

In the preceding discussion, we have considered oscillators using operational amplifiers with both positive and negative supply voltages. The results are equally applicable if discrete transistors are used in the place of operational amplifiers to realize the finite gain amplifier. These amplifiers exhibit similar saturation characteristics as that of operational amplifiers. However if there is only one power supply voltage (positive or negative), then the control can be applied on that voltage with a proper polarity. If, for example, the oscillator uses only a positive supply voltage then the inverter in Fig. 8 can be eliminated and the output of differential amplifier 2 can be directly connected to the oscillator as its power source.

VI. Standard-Signal Generators

Standard-signal generators find important applications in measurements [2], [3]. They are widely used in testing of radio receivers, in measuring standing wave ratio, signal to noise ratio, etc. In such generators, it is necessary to vary the carrier frequency without affecting the modulation index.

It is observed from the preceding sections that under ideal conditions the amplitude of oscillations will be equal to V_{R1}. Owing to imperfections in the components the amplitude may not be exactly equal to it. However, it should be noted that the relation between the amplitude and the reference voltage V_{R1} will remain linear. Thus the circuit can be used to generate stabilized amplitude modulation.

The oscillator is first set to generate the carrier frequency whose amplitude is stabilized by a dc voltage in place of V_{R1}. Because of stabilization, variation of carrier frequency will not change the carrier amplitude. The modulating signal is then applied in series with the dc voltage to get stabilized amplitude modulated wave. Fig. 10 is a photograph of 1-kHz carrier modulated by 100 Hz for a 50-percent modulation index. Since the carrier amplitude is stabilized, it is now possible to vary the carrier frequency without affecting the modulation index.

In the example above, a carrier frequency of 1 kHz has

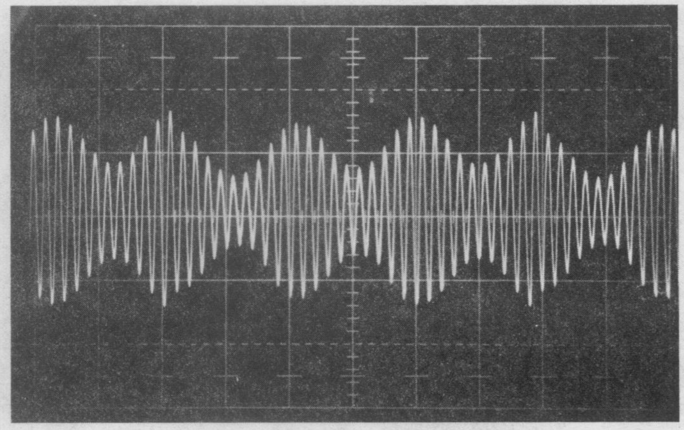

Fig. 10. Amplitude modulated carrier. Carrier = 1 kHz. Modulating signal = 100 Hz. Vertical scale = 2 V/Div.

been used. However, a radio-frequency carrier can be used easily by replacing the 1-kHz oscillator with a radio-frequency oscillator and by redesigning the peak detector only. The rest of the circuits will remain the same since the signals at these stages are of low (modulating) frequency.

VII. Conclusion

A simple feedback scheme for controlling the amplitude of oscillators by means of a voltage has been described. The control is precise and linear. Two applications of the scheme have been considered; one in amplitude stabilization of oscillators and the other in generation of stabilized amplitude modulation. The experimental results agree closely with theoretical predictions.

In the examples discussed in the paper, the scheme stabilized the amplitude of oscillation against variations with respect to frequency. However the stabilization will remain effective against variation due to other parameters such as temperature, loading, etc. It should also be noted that the voltages V_{R1}, V_{R2}, and the gain A are the only parameters that may need adjustment as we move from one oscillator to another. Thus by providing terminals for V_{R1} and V_{R2} and a potentiometer control for A, the feedback part of the circuit can be mass produced and easily adapted to different oscillators. Finally, the scheme, though presented for sinusoidal oscillators, should be applicable for other types such as square wave oscillators as well.

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Precision Model for Microwave Rotary Vane Attenuator

TOM GULDBRANDSEN

***Abstract*—A model for a rotary vane attenuator is developed to describe the attenuator reflection and transmission coefficients in detail. All the parameters of the model can be measured *in situ*, i.e., without disassembling any part. The transmission errors caused by internal reflections are calculated from measurements of the much larger reflection parameters, hence commonly used nonprecision instruments can be used to determine the transmission errors with sufficient accuracy for the highest precision obtainable in standard laboratories.**

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I. Introduction

IT IS WELL KNOWN that rotary vane attenuators (abbreviated RVA) are widely used for microwave attenuation measurements. This is due to the direct and accurate reading of the attenuation and to the rather constant (attenuation independent) phase shift.

Commercially available RVA's typically have an accuracy of $\pm(0.1$ dB + 1 percent of decibel reading) and $\pm 2°$ phase change up to 50 dB. Although this is sufficient for many purposes, some standard laboratory measurements require much higher precision.

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