A NOVEL HARMONIC BALANCING BRIDGE FOR CHARACTERISING MICROWAVE MODULES FOR PHASED ARRAY ANTENNA SERVICE

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ABSTRACT

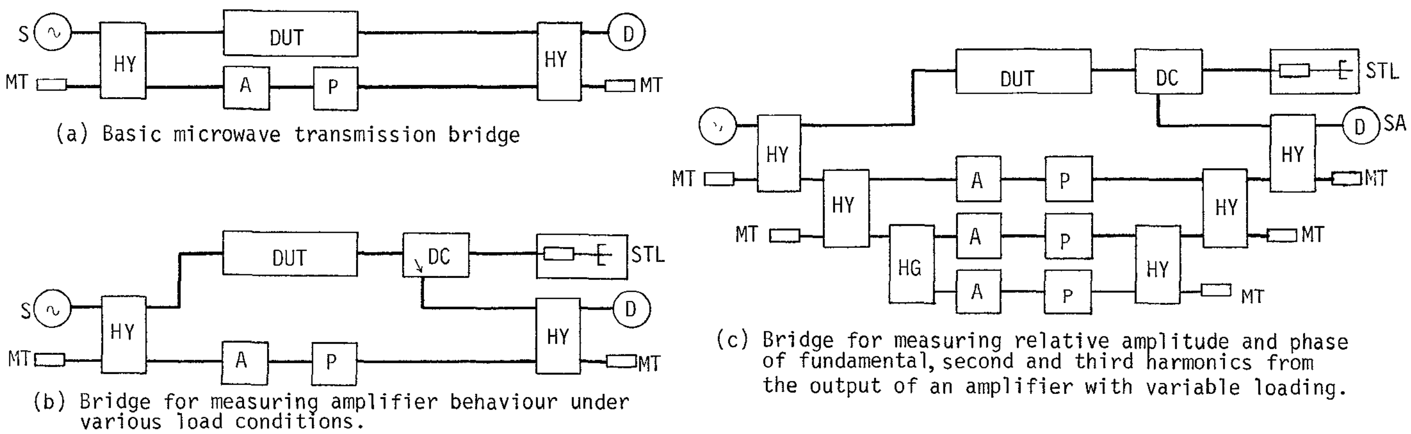
A novel microwave bridge incorporating fundamental and harmonic balancing has been developed for measuring amplitude and phase characteristics of items, such as phased array antenna amplifiers, that exhibit small but significant nonlinear behaviour. Measured characteristics relate to the output travelling waves from the item which may, however, be terminated in any safe load. Successful bridge design and operation in a fundamental range of 2 to 4 GHz, a second harmonic range 4 to 8 GHz and a third harmonic range 6 to 12 GHz has been achieved. Sensitivity and resolution are such that it is possible to differentiate between leading and trailing edge phase characteristics of pulse operated microwave amplifiers. Results obtained with various load impedances can be used to plot equi-amplitude and equi-phase contours on a Smith chart at fundamental and harmonic frequencies.

Introduction

Large numbers of microwave modules are required in the construction of phased array antennas and special testing arrangements are necessary to fully characterise the modules for their microwave operating environment arising from such systems requirements as beam scanning, pulsed operation, frequency chirping, etc. The measurement task is made particularly difficult for suppliers of this large market if suppression of out of band emissions, and harmonics in particular, to meet regulations is a system requirement specified in radiation pattern terms but allocated as a problem for solution to the module designer. The radiation pattern for each frequency component from a phased array antenna is determined by the relative amplitude and phase of each component of excitation at the input of each antenna element together with the load impedance presented by each element at each frequency. The load impedance is also a function of beam scanning, a problem that originates in the antenna. Due to imperfect isolation, the excitation components generated by the active modules associated with the elements are affected by the load impedance. The task then is to measure the relative amplitude and phase of all important excitation components as a function of load impedance for realistic scan ranges.

Choosing the measurement method

Conventional microwave instruments are not suitable for measuring the relative amplitude and phase of harmonically related components over the dynamic range relevant to phased array antenna operation. Microwave network analysers measure small signal scattering parameters and their basic role is the characterisation of components within the linear range of their behaviour. Microwave spectrum analysers measure relative amplitudes but do not measure relative phase. Microwave oscilloscopes measure waveforms and the relative amplitudes and phases of harmonically related components can be obtained by Fourier analysis, but the method is too inaccurate to give useful results for the relatively small harmonic amplitudes that are important in phased array antenna applications. Microwave bridges are usually assembled from individual components for operation at a single frequency or a succession of frequencies within a range. The operating principle of measuring the relative amplitude and phase of an unknown signal by nulling it with a known adjustable reference signal leads to accurate and sensitive measurements if the null is detected carefully. It is possible to develop this method and implement it with hardware for measuring the relative amplitudes and phases of harmonically related frequency components.



(a) Basic microwave transmission bridge

(b) Bridge for measuring amplifier behaviour under various load conditions.

(c) Bridge for measuring relative amplitude and phase of fundamental, second and third harmonics from the output of an amplifier with variable loading.

Figure 1. Simplified block diagrams of microwave transmission bridges showing the evolution of the harmonic balancing bridge.
Key: S, source; HY, hybrid; DUT, device or amplifier under test; DC, directional coupler; STL, standard test load; MT, matched termination; A, calibrated variable attenuator; P, calibrated variable phase shifter (usually line stretcher); HG, harmonic generator and filtering; SA, spectrum analyser; D, detector.

A novel harmonic balancing bridge has been designed, assembled and successfully used for characterising microwave modules for phased array antenna service.

The microwave harmonic balancing bridge

An elementary microwave transmission bridge is shown in Figure 1(a). Settings of the calibrated attenuator (A) and phase shifter (P) that yield nulls, before and after insertion of the device under test (DUT), can be used to determine the insertion characteristics of the DUT. To measure the output behaviour of an amplifier in response to load variations the modified bridge shown in Figure 1(b) can be used. The amplifier has a variable standard test load (STL) connected to its output. A small accurately known fraction of the outward travelling wave from the amplifier (DUT) is obtained from a directional coupler placed between it and the STL. The amplitude and phase of that travelling wave are the unknowns measured with the bridge and they can be determined as a function of the STL impedance and plotted as equi-amplitude and equi-phase contours on a Smith chart. The bridge operates satisfactorily with a small fraction of the amplifier output because the amplifier gain compensates in part or full for the coupling factor of the directional coupler. Results obtained are a study of the influence of load impedance on the outward travelling wave, and through them, effects arising within practical amplifiers can be measured separately from the effects that reflection from the load have on the resultant excitation of the load. Figures 2 to 5 show outflow quantities v. load.

Low-level non-linearity is an important effect for study within amplifiers because it gives rise to harmonics, and it too can be affected by the load on practical amplifiers. These harmonics are part of the amplifier output signal and can be measured with the same accuracy as the fundamental, if the STL and the directional coupler have known acceptable performance over a large enough frequency range and additional reference signals at the harmonics of the fundamental are available via separate controllable paths for nulling the ones present in the amplifier outward travelling wave. Figure 1(c) shows the essential features of a microwave bridge that can be balanced at the fundamental and its second and third harmonics. A spectrum analyser is used as the fundamental and harmonic null detector, supplemented by an oscilloscope when pulsed operation of the DUT is involved. The hybrids that combine all of the reference signals and the sample of outward wave from the amplifier must have known wideband performance. Also the inputs for the second and third harmonic reference paths must be related in a stable way to the fundamental reference. Their levels can be 10 to 20 dB below the fundamental and still be large enough to null harmonics produced by the worst of microwave amplifiers. Harmonic generation with an overdriven travelling wave tube amplifier is a satisfactory source. Well-matched accurately calibrated line stretchers, as used in network analyser test units, are suitable for measuring phase in the reference paths.

Finally the STL must be known at each frequency over its range of variation so that accurate and correctly related plots of all of the amplitudes and phases can be made on Smith charts. A coaxial wide band attenuator in cascade with an adjustable calibrated coaxial short circuit is suitable. The attenuator setting corresponds to a particular VSWR circle and movement of the short circuit moves the load impedance around that circle by some phase angle at the fundamental and by twice that angle at the second harmonic or three times at the third harmonic.

Measurements on phased array antenna amplifiers

The measurement procedure has several aspects which are best explained by reference to applications of bridges designed for studying microwave power amplifiers used in phased array antennas. The fundamental frequencies of operation were in the ranges 1 to 1.5 GHz for testing 60W L-band amplifiers and 2 to 4 GHz for testing various S-band units including a 25W bipolar transistor amplifier and three different TRAPATT amplifiers. Firstly, with the aid of band-pass filters, chart recordings of power outflow at

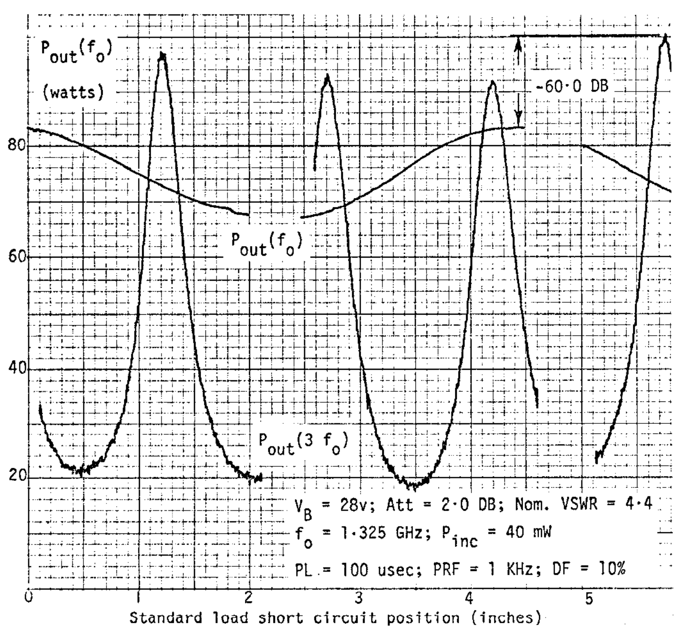
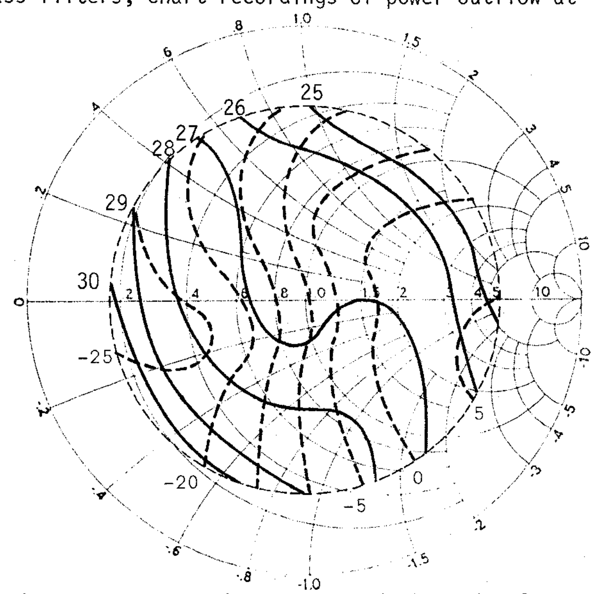


Figure 2. Power of the fundamental and the third harmonic wave from the output port of L-band module SN29M as a function of the position of the short circuit in the standard load.



Equi-power contours in watts, equi-phase in electrical degrees, f_0=3.3GHz, pulse length 100 microsecs and PRF 1kHz.

Figure 3. Power (continuous curves) and relative phase (broken curves) of the fundamental wave from the output port of S-band module SN99 as a function of the load impedance at the fundamental.

each frequency as a function of the STL short circuit position were made. These recordings show periodicity because movement of the short circuit corresponds to movement around a VSWR circle on the Smith chart and the periodicity indicates whether the harmonic power is a function of the load at that harmonic or the load at the fundamental frequency. Figure 2 shows recordings of fundamental and third harmonic power superimposed and it is evident that the latter is a function of the load at the third harmonic. Secondly, the bridge is balanced first at the fundamental and then successively at second and third harmonic until the low level residuals are left in the spectrum analyser display. Thirdly, with pulsed operation the device output spectrum about the fundamental and each harmonic will differ from that in the reference path. Balancing the bridge then involves observation of the resultant in both the frequency and the time domain, i.e. on the spectrum analyser and the oscilloscope respectively, as the reference is adjusted in phase and amplitude. A null can often be achieved over a frequency range that is only part of the extent of the spectrum, around say the fundamental, and as the reference phase is altered that null may move through the spectral distribution. Simultaneously on the oscilloscope, a minimum or broad notch at the leading edge of the pulse display may move to the trailing edge.

Figures 3 to 5 are equi-power and equi-phase contour plots on Smith charts. Power and phase values are obtained at sequences of points around VSWR circles and by interpolation between the points the contours are obtained. Figure 3 shows results for the fundamental in the outward travelling wave from a pulsed bipolar transistor type S-band amplifier. Available power ranges from 25 to 30 watts peak pulse level and the phase changes over a 30 degree range with load change. The mechanisms responsible for the behaviour shown by these contours are within the amplifier and may be due to the effect of the load changes on the operation of the class C type output power amplifier. The module incorporates a receiver path and imperfections in the T-R switches could provide feedback which would influence transmitter output behaviour. Supplementary tests would be needed to identify the causes of behaviour shown in Figure 3.

Figure 4 shows results for the second harmonic from the same S-band amplifier. Available power ranges from 37 to 45 DB below the maximum fundamental power shown in Figure 3 and the phase of the second harmonic changes over a 45 degree range. As with the fundamental behaviour, the detailed mechanisms that cause the results shown are internal to the amplifier and are most likely a result of non-linearity associated with the class C operating stage.

Figure 5 shows equi-phase plots only. One set applies to the leading edge of the outflow pulse from an L-band amplifier and the other set to the trailing edge of the pulse. Derivation of these results involves nulling with both spectrum analyser and oscilloscope displays. As a practical interpretation of the spectral distribution around the fundamental output it is indicative of the complexity involved in developing a model for this type of amplifier to represent load dependent behaviour.

Automating the measurement procedure

Balancing the bridge at successive harmonics is a complex procedure particularly when the DUT produces outflow spectra different in shape to those in the reference paths. Push button control of reference path elements and computer control of STL scanning and successive settings is practical and effective.

Reference

Griffin, Donald W., "Solid state array studies relevant to OTP regulations", Rome Air Development Center-TR-76-241, Aug. 1976, 226 pp.

Acknowledgement

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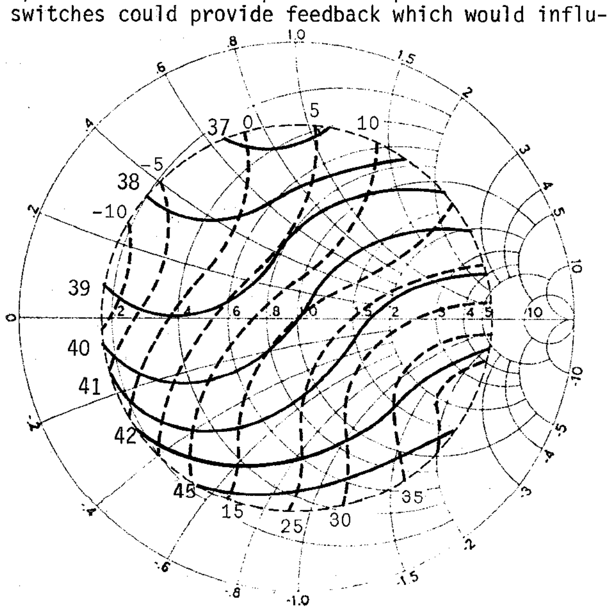
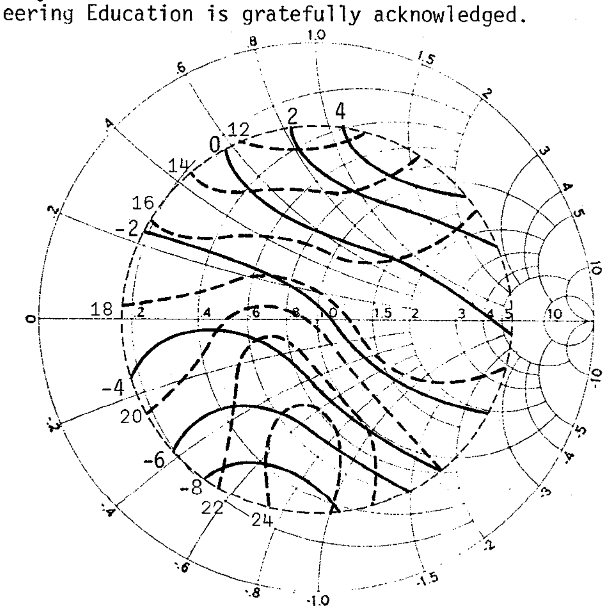


Equi-power contours in DB below maximum fundamental, pulse length 100 microsecs and PRF 1 kHz.

Figure 4. Power (continuous curves) and relative phase (broken curves) of the second harmonic wave from the output port of S-band module SN99 as a function of the load impedance at the fundamental.



f_0=1.325 GHz, pulse length 100 microsecs and PRF 1 kHz.

Figure 5. Equi-phase plots in electrical degrees for the leading (continuous curves) and the trailing (broken curves) edge of the amplifier output pulse. Fundamental wave outflow from L-band module SN73M.