Title: LOSS-COMPENSATING CIRCUIT

Abstract: Loss-compensating circuit for use when analysing electrical properties, such as large-signal properties, of an electronic device to be tested (1) by means of an impedance tuner (6; 7). The loss-compensating circuit (15) comprises two symmetrically positioned negative impedance elements (26, 27) separated by a phase shift network (17; 28; 30). By this means the losses between the tuner (6; 7) and the electronic device (1) are at least compensated in a predetermined frequency band around an operating frequency of the loss-compensating circuit (15).
For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.
Loss-compensating circuit

Field of the invention

The present invention relates to a loss-compensating circuit for use when analysing electrical properties, such as large-signal properties of an electronic device to be tested by means of an impedance tuner. This characterisation takes place by means of measuring the electronic properties of the component under test (CUT) when various specific impedances are applied to the input and output of the CUT. The measurement technique described here is also referred to as 'load-pull' measurement technique. If specific impedances are supplied not only at the operating frequency but also at the mixed products of the existing frequency components there are said to be harmonic 'load-pull' measurements. The application of the specific impedances to the CUT is implemented by means of an impedance tuner. The said circuit can be in the form of an electronic filter, a network of electronic components or a multiple port circuit.

State of the art

In current load-pull set-ups the tuners are implemented mechanically (passively) or actively. Passive tuners have the disadvantage that they introduce electrical losses into the measurement system which significantly limits the maximum achievable reflectance that can be applied to the CUT (for passive networks the reflectance is < one). As a result, in practice only impedance values within a limited range can be generated by the tuner, which imposes a severe restriction on the usability/applicability of the load-pull measurement.

In the case of an active implementation of the electric tuners, the losses in the measurement system can be compensated for. However, such active systems have the disadvantage that these have a complex construction and consequently are expensive. Furthermore, such active systems, which frequently make use of feedback loops, introduce long Transfer times, as a result of which some types of measurements with broadband modulated signals cannot be carried out.

Summary of the invention

The present invention aims to provide a solution to the problems outlined above. According to the present invention a loss-compensating circuit according to the type defined in the preamble is provided, wherein the loss-compensating circuit comprises two
symmetrically positioned negative impedance elements separated by a phase shift network, in order at least to compensate for losses between the tuner and the electronic device in a predetermined frequency band around an operating frequency of the loss-compensating circuit. The loss compensation envisaged is based on the use of negative impedance elements separated by a phase shift network.

In its most simple embodiment a $\lambda/4$ transmission line is positioned between two negative impedance elements, where $\lambda$ is the wavelength that corresponds to the operating frequency of the device to be tested (or component under test CUT). With this network structure the reflectance $\Gamma_T$ is transformed uniformly and symmetrically with respect to the origin over the entire range of the tuner to the CUT reference surface by the loss-compensating circuit. This is important in the case of 'load-pull' measurements because this enables amplification of the absolute value of the reflectance independently of its phase, which in practice is a significant advantage for usability. Note that in the usual case the loss-compensating circuit and the tuners will display certain losses, which, however, are (over)compensated by the negative impedance elements according to the invention that are present. As a result of this overcompensation, compensation of the other losses occurring in the measurement set-up is possible, as a result of which better and more reliable measurements can be carried out over a large impedance range. By correct selection of the values of the negative impedance elements, the absolute value of the reflectance of a passive tuner, which usually is restricted to a value of less than one, can be transformed by the loss-compensating filter into an amplified reflectance with an absolute value greater than one. The desired reflectance that is applied to the CUT can be selected by means of a passive tuner. The technique described, implemented as a loss-compensating filter, has the additional advantage that the DC path (which is needed for powering the CUT) is automatically separated from the RF path, which makes the use of a bias network unnecessary, as in the test set-up according to the state of the art described above. This is a significant advantage if it is also desired to terminate the CUT correctly with a suitable impedance on the "intermediate frequency" (IF) or difference frequency; in practice the latter has a substantial influence on the linearity of the CUT.

A loss-compensating circuit that makes the use of a bias network unnecessary can be made up in accordance with the following embodiment. The loss-compensating circuit is of the "directional travelling wave" type and comprises a first $\lambda/4$ transmission line with a first connection and a second connection, a second $\lambda/4$ transmission line with a third
connection and a fourth connection, a coupling element with four transmission lines, two
transmission lines of which are positioned parallel to the first and the second transmission
line, respectively. The electronic device to be tested (CUT) can be connected to the first
connection, the tuner can be connected to the third connection and a terminating impedance
corresponding to the system impedance can be connected to the fourth connection. The
negative impedance elements are connected to the coupling element at the level of the first
and the third connection. Such an implementation of the loss-compensating circuit can be
produced very easily and inexpensively. The DC supply for the CUT can be applied to the
second connection.

The negative impedance elements can also be positioned at another location. In this
further embodiment the loss-compensating circuit has a microwave filter and an additional
loss-compensating section. The additional loss-compensating section comprises two
negative impedance elements and a $\lambda/4$ transmission line positioned between the negative
impedance elements.

In a further embodiment of the present invention several loss-compensating circuits
connected in a cascade can be connected to the second connection, each loss-compensating
circuit connected in cascade having a different operating frequency. Each loss-
compensating circuit connected in cascade can have (but does not have to have) an
operating frequency that is an integer multiple of a base frequency. By this means it is
possible in a very simple manner to create a measurement set-up with which the device to
be tested is subjected to multiple (harmonic) impedance terminations.

According to the present invention, the negative impedance elements can, for
example, be tunnel diodes or Gunn diodes (low power application), IMPATT diodes
(medium power application) or transistors with positive feedback, such as an LDMOS
transistor, HEMT or PHEMT (high power application). These elements are known to those
skilled in the art and can be selected depending on the field of application (power,
frequency).

**Brief description of the drawings**

The present invention will now be discussed in more detail on the basis of a number
of illustrative embodiments, with reference to the appended drawings, in which

Fig. 1 shows, diagrammatically, a 'load-pull' measurement set-up;

Fig. 2 shows, diagrammatically, a first embodiment of a loss-compensating circuit in
a load-pull configuration;

Fig. 3 shows, diagrammatically, a second embodiment of a loss-compensating circuit according to the present invention;

Fig. 4 shows a further embodiment of a loss-compensating circuit in a directional implementation;

Fig. 5 shows a frequency multiplexing filter implementation where the loss compensation is implemented as external section for the individual harmonics;

Fig. 6 shows, diagrammatically, loss-compensating filters connected in cascade; and

Fig. 7 shows a Smith chart that displays characteristics for an example of the transformation by the loss-compensating filter according to the present invention.

**Detailed description of illustrative embodiments**

A loss-compensating circuit 15 (in the form of, for example, a filter or an electronic network) according to the present invention can, in particular, be used when measuring the electrical characteristics of a component under test (CUT) 1, the CUT 1 being subjected to specific signals at different termination impedances in order to measure the behaviour of the CUT 1 (for example amplification, linearity or power supplied). These measurements are also referred to by the term 'load-pull' measurements. In the majority of cases the components to be tested (such as a power transistor used in telecommunication systems) have a low input impedance (a few Ω), whilst most test equipment is equipped with a standard output impedance of, for example, 50 Ω. The CUT 1 frequently has a non-linear behaviour which is dependant on the power, the operating frequency and the impedances applied to the CUT and this makes physically applying the correct conditions of essential importance for a sensible component characterisation.

Fig. 1 shows an example of such a 'load-pull' measurement set-up. The CUT 1 is in a test set-up 2. A signal source 3 supplies a signal that is used for the test. By means of a coupling element 5 it is possible to measure the signal from the signal source 3 accurately, for example using input power meter 4. Optionally, the power reflected back by the device to be tested 1 can also be measured in a similar manner via a coupling component by a power meter. By means of a passive input tuner 6 the signal source impedance is tuned to the requisite value for the device to be tested 1 at a specific operating frequency. On the output side the output signal is processed by a (passive) output tuner or output tuner 7 (that tunes the input impedance of the output power meter 8 to the requisite value) for
measurement by output power meter 8. Various characteristics can be derived from the absolute values and ratios of the values of input power and output power (and/or reflected power).

For correct measurement the values of the powers would have to be known directly at the input surface and output surface of the device to be tested 1. However, in practice the various components of the test set-up are connected to one another by cables, connections and couplings, such as a link 10 between input tuner 6 and device to be tested 1 and a link 11 between the device to be tested 1 and output tuner 7. These cables, connections and couplings give rise to losses and reflections and have an influence on the electrical behaviour of the test set-up. As a result of the losses and reflections that occur and the resulting distortions of the test signal it can be the case that not all test parameters of interest can actually be tested.

According to the present invention this problem is solved by inserting a loss-compensating circuit 15 in the links 10 and or 11. Embodiments of loss-compensating circuits 15 are shown diagrammatically in Fig. 2, 3, 4, 5 and 6 and contain loss-compensating elements that are separated by a phase shift network.

The simplest embodiment of the loss-compensating circuit 15 is shown in Fig. 2. The loss-compensating circuit 15 consists of a negative impedance 26 connected to a λ/4 transmission line 24 followed by a second negative impedance 27. Positioning this network between the CUT 1 and the "passive" tuner 6, 7 will compensate for the losses in the measurement system.

The above circuit is of simple design but is frequency selective to only a limited degree, which necessitates the use of a presetting network for supplying the electric power for the CUT 1.

The embodiment of the loss-compensating microwave filter 15 shown in Fig. 3 is in fact a microwave filter consisting of two directional couplings that are connected to one another by two λ/4 transmission lines. The microwave filter has a first λ/4 transmission line 16 with a first and a second connection 21, 22, a second λ/4 transmission line 17 with a third and a fourth connection 23, 24 and a coupling element 18. The coupling element 18 consists of λ/4 transmission lines positioned in a square configuration, two of which transmission lines are parallel to the first and the second transmission lines 16, 17, respectively. If impedances 26, 27 in Fig. 3 are left out of consideration, it is clear that the loss-compensating filter 15 is a directional filter. Because all transmission lines 16, 17, 18
have an electrical length of $\lambda/4$, where $\lambda$ is the wavelength at the operating frequency of the loss-compensating filter 15, all the power within a specific (narrow) bandwidth around the operating frequency of the first connection 21 will be coupled to the third connection 23, whilst the other connections 22, 24 are isolated. For all other frequencies the power is coupled to connection 22. The fourth connection 24 is always isolated when this has been terminated in the correct manner.

In the measurement set-up the passive input tuner 6 is connected to the third connection 23 and a terminating impedance 25 (for example 50 $\Omega$) corresponding to the system impedance is connected to the fourth connection 24. The loss-compensating filter 15 according to the embodiment of the present invention shown in Fig. 3 furthermore comprises two negative impedance elements 26, 27 that compensate for, or even overcompensate for, the losses in the test set-up. These negative impedance elements 26, 27 ensure uniform and symmetrical transformation of the reflectance of the input tuner 6 to the CUT reflection surface.

In the embodiment shown the negative impedance elements 26, 27 are connected to the coupling element 18 at locations that correspond to the first connection 21 and the third connection 23, respectively. However, it is possible to connect the negative impedance elements 26, 27 (at the cost of the uniform/symmetrical GAMMA transformation) at other locations in the diagram, provided there is a $\lambda/4$ transmission line between the two negative impedance elements 26, 27.

The latter also applies for the embodiment shown in Fig. 4, where the loss-compensating section has been positioned outside the actual directional coupling of the filter. A uniform symmetrical GAMMA transformation can also be achieved by this means.

Note that in principle the filter structure can be freely chosen provided a loss-compensating section is added in each frequency path between the filter and the tuner to be connected. Such an embodiment is shown in Fig. 5, where three tuners at different frequency are connected to a conventional frequency-multiplexing filter 29. The loss-compensating sections have to be designed for the frequency concerned.

The negative impedance elements 26, 27 must be frequency-selective insofar as these must only generate energy in the passband of the loss-compensating filter 15. Otherwise, undesired oscillations could arise outside the frequency band.

Various elements known to those skilled in the art can be used as negative impedance elements 26, 27, such as tunnel diodes or Gunn diodes (for low power applications),
IMPATT diodes (for medium power applications) or transistors with a positive feedback (for high power applications, LDMOS, HEMT or PHEMT).

In a test set-up it has been found that with LDMOS transistors as the basis for the negative impedance elements 26, 27 a usable practical solution in a wide range of load conditions is offered. If the power demands threaten to become too high for a specific test environment, for example in the case of very low load impedance of the device to be tested 1, it is possible to make a pre-adjustment. The influence of this pre-adjustment can be taken into account in the final measurement results.

The loss-compensating filter 15 discussed will transform the reflectance of the input tuner 6 in a very uniform manner, it then being possible (if desired) to achieve an amplified reflectance with an absolute value of more than one. This is achieved in a simple and cost-effective manner. Because of the limited electrical delay time of the loss-compensating filter 15 compared with current implementations of active load-pull systems it is possible to keep the frequency dependence of the reflectance at the CUT very low. As a result, the test signal supplied by the signal source 3 for a specific application (for example WCDMA applications) can be chosen to be sufficiently broadband and a realistic circuit situation for the CUT can be imitated.

The diagrammatic representation of the simple embodiment shown in Fig. 2 is to be regarded as the equivalent circuit of the circuit shown in Fig. 3 at the design or base frequency $f_0$. At the base frequency $f_0$ all power from the first connection 21 is coupled to the third connection 23. Because the circuit has a passive, reciprocal structure, incident power on the third connection 23 will be coupled to the first connection 21. The equivalent circuit thus consists of a simple transmission line 28 between the first and third connection 21, 23 with an electrical spacing of $\lambda/4$ between the two negative impedance elements 26, 27.

For the equivalent circuit in Fig. 2 the dual port S parameters can be derived as

$$S_{12} = S_{21} = \frac{-2j}{(1 + Y)^2 + 1}; \text{ and}$$

$$S_{11} = S_{22} = \frac{-Y^2}{(1 + Y)^2 + 1}$$

where $Y$ is the normalised admittance of the negative impedance elements 26, 27 (for example in the case of negative resistors of value $R \bar{Y} = \frac{V}{Y_0}$, where $Y_0$ is the...
characteristic admittance of the transmission line 28).

The reflectance $\Gamma_{out}$ indicated in Fig. 2, as seen by the device to be tested 1, can be written as

$$\Gamma_{out} = S_{11} + \frac{S_{12}S_{21}\Gamma_T}{1 - S_{22}\Gamma_T} = \frac{S_{11} - \Delta\Gamma_T}{1 - S_{22}\Gamma_T}$$

where $\Delta$ is the determinant of the $S$ matrix ($\Delta = S_{11}S_{22} - S_{12}S_{21}$). This equation has the known form of a bilinear transformation. A well-known property of bilinear transformations is that circles are displayed as circles in the complex plane. It can be derived from the above equation that the circle displayed will fall with a midpoint at the value $S_{11}$. This value (and thus the normalised value $\bar{\Gamma}$ of the negative impedance elements 26, 27) will thus have to be kept small in order to keep the circle displayed in the centre of the Smith chart. Depending on the circumstances (for example desired reflectance $\Gamma_{out}$), the requisite values for the negative impedance elements 26, 27 can be obtained from these equations for a specific reflectance $\Gamma_T$ of the input tuner 6. One example teaches that for an input tuner 6 for which $|\Gamma_T| = 0.9$, the reflectance $\Gamma_{out}$ for the device to be tested 1 a specific maximum reflectance value can be reached. An assessment can then be made as to whether the associated normalised admittance $\bar{\Gamma}$ gives rise to a permissible shift in the circle displayed or whether this has to be chosen to be smaller (and consequently a lower absolute value of the reflectance for the device to be tested 1 is obtained). It is also possible to determine which normalised admittance $\bar{\Gamma}$ is needed to compensate for specific losses. In the example given above of the reflectance of the input tuner 6 and a loss of 6 dB to be compensated, the requisite normalised admittance $\bar{\Gamma}$ is 0.45.

An example of the Smith chart for the transformation of the loss-compensating filter 15 in the abovementioned example is given in Fig. 7. The inner closed ring shows the reflectance of the input tuner 6. The outer open points show the reflectance for the device to be tested 1, which form a circle that is slightly asymmetrical with respect to the imaginary axis. However, the asymmetry is acceptable and the entire region of the Smith chart can be used.

In the example given actual values have been taken for the impedances 26, 27, as a result of which an asymmetry is produced with respect to the imaginary axis in the Smith chart. If the impedances 26, 27 have an imaginary part, the circle displayed will likewise display an asymmetry with respect to the real axis.
A disadvantage of the loss-compensating filter 15 according to the present invention is a fixed design or base frequency. This thus requires a separate filter 15 that is adapted for a specific application. However, because of the simple and cost-effective construction of the present loss-compensating filter, this does not have to constitute a disadvantage.

A cascade circuit of two loss-compensating filters 15, 15' is shown in simplified form in Fig. 6. The first loss-compensating filter 15 operates at a base frequency \( f_0 \), with an associated first input tuner 6, and the second loss-compensating filter 15' functions on a harmonic of the base frequency \( f_0 \), for example \( 2f_0 \). Matched \( \lambda/4 \) transmission lines are used at the individual filter sections, as well as matched values of the negative impedance elements 26', 27'. A multiplicity of loss-compensating filters can be connected one after the other in a cascade in a similar manner (the highest harmonic frequency comes first). This embodiment can be employed in particular in harmonic 'load-pull' test set-ups where a device to be tested is subjected to specific impedance terminations at the base frequency and also at one or more harmonic frequencies arising.
Legend for figures

Fig 1
1 = device to be tested
2 = test set-up
3 = signal source
4 = input power meter
5 = coupling element
6 = input tuner
7 = output tuner
8 = output power meter

Fig 2
1 = device to be tested

Fig 5
1 = CUT/device to be tested
29 = conventional frequency-multiplexing filter
CLAIMS

1. Loss-compensating circuit for use when analysing electrical properties, such as large-signal properties, of an electronic device to be tested (1) by means of an impedance tuner (6; 7), characterised in that the loss-compensating circuit (15) comprises two symmetrically positioned negative impedance elements (26, 27) separated by a phase shift network (17; 28; 30), in order at least to compensate for losses between the tuner (6; 7) and the electronic device (1) in a predetermined frequency band around an operating frequency of the loss-compensating circuit (15).

2. Loss-compensating circuit according to Claim 1, wherein a λ/4 transmission line (28) is positioned between the negative impedance elements (26, 27), where λ is the wavelength that corresponds to the operating frequency of the device to be tested (1).

3. Loss-compensating circuit according to Claim 1 or 2, comprising a first λ/4 transmission line (16) with a first connection (21) and a second connection (22), a second λ/4 transmission line (17) with a third connection (23) and a fourth connection (24), a coupling element (18) with four λ/4 transmission lines, two λ/4 transmission lines of which are positioned parallel to the first and the second transmission line (16, 17), wherein the electronic device to be tested (1) can be connected to the first connection (21), the tuner (6) can be connected to the third connection (23) and a terminating impedance (25) corresponding to the tuner (6) can be connected to the fourth connection (24), and wherein the negative impedance elements (26, 27) are connected to the coupling element (18) at the level of the first and the third connection (21, 23).

4. Loss-compensating circuit according to Claim 1 or 2, comprising a microwave filter section and an additional loss-compensating section that comprises two negative impedance elements (26, 27) and a λ/4 transmission line (30) positioned between the negative impedance elements (26, 27), where λ is the wavelength that corresponds to the operating frequency of the loss-compensating circuit (15).
5. Loss-compensating circuit according to Claim 1, 2, 3 or 4, wherein the loss-compensating circuit comprises several loss-compensating circuits (15, 15') connected in cascade, wherein each loss-compensating circuit (15, 15') connected in cascade has a different operating frequency.

6. Loss-compensating circuit according to Claim 5, wherein each loss-compensating circuit (15, 15') connected in cascade has an operating frequency that is an integer multiple of a base frequency.

7. Loss-compensating circuit according to one of Claims 1 to 6, wherein the negative impedance elements (26, 27) are constituted by an element from the group comprising: tunnel diode; Gunn diode; IMPATT diode; transistor with positive feedback; LDMOS transistor; HEMT; PHEMT.

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Fig 5

CUT / device to be tested

Conventional frequency-multiplexing filter

Tuner @ f₀
Tuner @ f₂
Tuner @ f₃

Fig 6

Tuner @ 2f₀
Tuner @ f₀
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 G01R1/067 G01R1/24 G01R27/32

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G01R H03H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Further documents are listed in the continuation of box C.

D. DATE OF ACTUAL COMPLETION OF THE INTERNATIONAL SEARCH

5 October 2004

E. DATE OF MAILING OF THE INTERNATIONAL SEARCH REPORT

11/10/2004

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HJ Rijswijk
Tel. (31-70) 340-5040, Tx. 31 651 epo nl, FAX (31-70) 340-3016

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Koll, H

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