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Abstract **- An overview of several hot S-parameter techniques is presented. It is shown that different definitions are in use, causing confusion among users. Different techniques are explained in a nutshell, together with their advantages and drawbacks. It is explained that any accurate hot S-parameter approach needs 6 parameters in contradiction with the classic small signal S-parameter approach where 4 coefficients are sufficient.**

Index Terms **– hot S-parameters, power amplifier measurements, large-signal characterization**

I. INTRODUCTION

Since the early 70's S-parameters have revolutionized the microwave industry. One of the main reasons is that they turn the design cycle significantly more efficient. That is because S-parameters completely and accurately describe the four main characteristics of any two-port device: transmission (S_{21}), output match (S_{22}), isolation (S_{12}) and input match (S_{11}). Although still considered by (too) many as omnipotent, S-parameters have one significant drawback: they are only valid under linear operating conditions. They can not be used to describe nonlinear distortions that are challenging todays amplifier designers like e.g. compression, AM-PM conversion, spectral regrowth,… . Recently several attempts have been made to extend the S-parameter concept into the nonlinear or "large-signal" domain [1]-[9]. The resulting parameters are called "Hot S-parameters" or "Large-Signal S-parameters". This paper gives an overview of the most popular existing techniques.

II. WHAT ARE "HOT S-PARAMETERS"?

In general all of the existing hot S-parameter techniques [1]-[9] have the purpose of describing how an amplifying device-under-test (DUT) interacts with previous and following signal processing stages (like e.g. amplifiers, mixers, modulators, synthesizers, antennas,…) under large-signal operating conditions. The DUT may be a complete high power amplifier system, a radio-frequency integrated circuit (RFIC), or a single power transistor. With large-signal operating conditions we refer to signal levels that are of the same order of magnitude as the operating range of the device. In practice this corresponds to operating the amplifying device with at least 1dB of compression. Some hot S-parameter techniques are valid all the way up to operating the DUT in full saturation. In all previous work, the hot S-parameter techniques are used for relatively narrowband applications. With this kind of applications the excitation signal can be described as a one tone signal, which may be modulated or not. As such, all hot S-parameter techniques can be considered as black-box frequency domain behavioral models. In some cases ([1] and [8]) only the effects of output matching is being considered and the hot S-parameter technique is limited to hot-S_{22} only.

Two major power amplifier design problems under hot operating conditions are targeted by the existing hot S-parameter techniques: distortion at the fundamental and stability.

III. STABILITY UNDER HOT OPERATING CONDITIONS

The use of hot S-parameters to investigate the stability of an amplifier under hot operating conditions is discussed in [1], [2] and [5]. The most detailed explanation is given in [5]. The idea is to put the DUT under realistic operating conditions by applying the appropriate large-signal stimulus signal. The applied signal is a one-tone signal or a modulated carrier. While this signal is being applied one injects a small one-tone signal first into the DUT signal port 1, this is called the forward measurement, and next in signal port 2, this is called the reverse measurement. Each time one measures the injected signal, which are called the a-waves, and the corresponding reflected waves, which are called the b-waves. Just as it is done with small signal S-parameters, the hot S-parameters are defined as the ratio's between the incident a-waves and the reflected b-waves. This process is illustrated in figure 1 and figure 2. Figure 1 illustrates the spectrum of the incident a-waves and the scattered b-waves during the forward hot S-parameter measurements and figure 2 illustrates the spectra of the incident a-waves and the scattered b-waves during a reverse hot S-parameter measurement. The large signal carrier is applied at a frequency f_C, and f_S denotes the frequency at which the hot S-parameters are being measured. The large signal carrier at frequency f_C is always present in the a-wave that is incident to the input port of the DUT (a_1), the small signal, the so called probe tone, is present in the a_1 wave during the forward measurement and is present in the a_2-wave during the reverse measurement. The hot S-parameters are defined by taking the ratio's between the b-waves and the a-waves at the frequency f_S in a way identical to classic small signal S-parameters. The definition of the hot S-parameters is given by the following equations.

$$hotS_{11} = \left.\frac{b_1(f_S)}{a_1(f_S)}\right|_{forward} \qquad \text{Eq.1}$$

$$hotS_{21} = \left.\frac{b_2(f_S)}{a_1(f_S)}\right|_{forward} \qquad \text{Eq.2}$$

$$hotS_{12} = \left.\frac{b_1(f_S)}{a_2(f_S)}\right|_{reverse} \qquad \text{Eq.3}$$

$$hotS_{22} = \left.\frac{b_2(f_S)}{a_2(f_S)}\right|_{reverse} \qquad \text{Eq.4}$$

The basic assumption for using the stability hot S-parameter theory is that the relationship between the a-waves and the b-waves at a frequency f_S is given by a classical S-parameter equation.

$$\begin{bmatrix} b_1(f_S) \\ b_2(f_S) \end{bmatrix} = \begin{bmatrix} hotS_{11} & hotS_{12} \\ hotS_{21} & hotS_{22} \end{bmatrix} \begin{bmatrix} a_1(f_S) \\ a_2(f_S) \end{bmatrix} \qquad \text{Eq.5}$$

The stability analysis is then performed as it is done with small signal S-parameters [10][11] and it is based on the calculation of the corresponding hot K-factor [1][5] or hot μ(source) and hot μ(load) [2]. The hot S-parameters of equation 5 are a function of both the amplitude and the frequency (f_C) of the large signal tone $a_1(f_C)$.
Note that the b-waves in figures 1 and 2 contain tones at frequencies different from f_S and f_C, namely at the sum frequency (f_C+f_S) and at the difference frequency (f_C-f_S). As explained in [5], there are even

more tones present in the b-waves, namely at the harmonics of the carrier and at their respective sum frequencies ($L.f_C+f_S$) and difference frequencies ($L.f_C-f_S$), with L being an arbitrary positive integer. All of the extra sum and difference frequency tones are mixing products between the probe tone at f_S and the fundamental and harmonics of the carrier at f_C. These mixing products are proportional to the probe tone and, as it is the case for the tones at a frequency f_S, there also exists a linear "S-parameter like" relationship as described by equation 5 between these mixing products and the probe tone. In practice, however, it is always assumed that these mixing products can be neglected for a stability analysis. This assumption is explicitly mentioned in [5], where it is explained that in practice stability is often investigated at frequencies f_S that are much lower than the typical carrier frequency corresponding to the application for which a DUT is designed. Under that assumption the interaction between the tones at a frequency f_S is much stronger than the interaction between all of the other tones appearing near the fundamental and harmonics of the carrier frequency, and the conclusions of any stability analysis will be accurate.

Any results of the above described hot S-parameter stability analysis whereby the probe frequency f_S is not significantly lower than the carrier frequency f_C should be interpreted with extreme caution because of the potential presence and mutual interaction between mixing products at frequencies ($L.f_C+f_S$) and ($L.f_C-f_S$), with L an arbitrary positive integer. In that case equation 5 is not valid.

Consider e.g. that one measures the hot S-parameters whereby f_S is equal to f_C divided by 2. In that case one of the mixing products will appear at a difference frequency f_C-f_S, which is equal to f_S! In that case the mixing product and the "direct reflection" (at a frequency f_S) will interfere with each other. As such one can expect that the hot S-parameter characteristic may behave irregular for an f_S close to f_C divided by 2. Under such circumstances the assumptions of the small signal stability analysis described in [10] and [11] are no longer valid and any conclusion related to stability must be taken with care.

The above principle of interference is nicely illustrated by Dunsmore et al. in [2]. Figure 3 represents the hot μ stability parameters as they were reported in figure 5 of [2], whereby f_C equals exactly 900 MHz. One can clearly see that one of the characteristics (μ_{source}) behaves irregular for values of f_S that are close to 450 MHz. This can most likely be explained by the above described interference between the mixing product at a frequency (f_C-f_S) appearing at the same frequency as the direct reflection at the frequency f_S. According to the hot S-parameter theory outlined above (neglecting this interference effect) one would expect the circuit to be unstable and to start oscillating at a frequency of about 450 MHz. The spectrum was actually measured by Dunsmore et al. under "unstable" matching conditions. The result is shown in figure 4 (figure 6 of [2]). The spectrum shows that, as predicted, a frequency component is indeed present at 450 MHz. When one takes a closer look at the spectrum one does note, however, that the oscillation has peculiar characteristics that are unusual for unstable behavior described by classical circuit stability theory. First of all the oscillation frequency appears to be exactly 450 MHz (see marker on figure 4), precisely one half of the carrier frequency. Another interesting feature is that the oscillation amplitude is very low, less than 40 dB below the amplitude of the carrier. The amplitude of an instability in the classical sense grows exponentially until the amplitude is stabilized by some limiting mechanism like saturation. It is unlikely that such a limiting mechanism kicks in at such a low power level. The above facts indicate that the observed signal at 450 MHz in figure 4 (figure 6 in [2]) is likely not an oscillation caused by an instability, but that it is rather a stable subharmonic of the carrier that is being generated by the DUT.

IV. HOT S-PARAMETERS PREDICTING DISTORTION CHARACTERISTICS

Besides analyzing the stability properties under hot conditions, another goal of hot S-parameters is to predict distortions caused by the DUT when it is cascaded with other components [3][4][6][7][8]. By our knowledge, all hot S-parameter techniques that have been developed for this purpose are aimed towards narrowband system level applications. In these application the input signal is described as a one tone carrier, which may be modulated at a rate that is slow when compared to the carrier frequency. It is also assumed that the DUT is operating in a near matched environment. In such systems energy in the a-waves and b-waves is only expected to be present at the fundamental frequency and the harmonic frequencies of the carrier. Since no other frequencies are present, it will be sufficient to describe the interaction between a-waves and b-waves at the limited set of frequencies described by $L.f_C$, with L an arbitrary positive integer. This is illustrated in figure 5. Since the matching conditions are close to the characteristic impedance that is used for defining the a-waves and the b-waves (usually 50 Ohm), one can assume that all of the tones appearing in the a-waves are small, with the trivial exception of the large signal $a_1(f_C)$ tone. Since the tones $a_1(2f_C)$, $a_1(3f_C)$,…,$a_2(f_C)$, $a_2(2f_C)$, $a_2(3f_C)$,… are small when compared to the large signal tone $a_1(f_C)$ their interaction with the b-waves can be described by a linear S-parameter like relationship. A complete solution to the above stated problem is given by the "Poly-Harmonic Distortion" behavioral model, which is described in detail in [4]. In practice simplified approaches are often used. A first simplification is the exclusion of interactions that happen at the harmonic frequencies $2f_C$, $3f_C$,… . Such a simplified fundamental-only approach is described in [3][6] and [8]. In the following we will only consider these fundamental-only hot S-parameter approaches. A simple and intuitive extension of small signal S-parameters to hot S-parameters is used in the Advanced Design System simulator of Agilent Technologies. It is implemented by using a "Large-Signal S-parameter Simulation" component, also called the "LSSP Simulation Controller" [3]. The main idea is that the relationship between the incident a-waves and the reflected b-waves is described by the following equation.

$$\begin{bmatrix} b_1(f_C) \\ b_2(f_C) \end{bmatrix} = \begin{bmatrix} hotS_{11} & hotS_{12} \\ hotS_{21} & hotS_{22} \end{bmatrix} \begin{bmatrix} a_1(f_C) \\ a_2(f_C) \end{bmatrix} \quad \text{Eq.6}$$

In equation 6 the hot S-parameters are a function of both the amplitude and the frequency of the large signal $a_1(f_C)$. Although very similar to equation 5, the above equation 6 is fundamentally different in nature since it is nonlinear in the incident wave variable $a_1(f_C)$, unlike equation 5, which is perfectly linear in the incident wave variable $a_1(f_S)$. Note, however, that equation 5 as well as equation 6 are linear in a_2. The hot S-parameter approach of equation 6 can accurately describe the nonlinear transmission characteristics of a DUT (the compression and the AM-PM characteristic) and its nonlinear input match. As explained in [7] and [8] inaccurate results may be obtained for describing the nonlinear output matching characteristic (hot S_{22}) and the nonlinear isolation characteristic (hot S_{12}). This inaccuracy can be attributed to the fact that the simple and intuitive extension of hot S-parameters as described by equation 6 lacks the presence of the conjugate $a_2(f_C)$ tone. As shown in [6]-[8] a scientifically sound extension of hot S-parameters looks as follows.

$$\begin{bmatrix} b_1(f_C) \\ b_2(f_C) \end{bmatrix} = \begin{bmatrix} hotS_{11} & hotS_{12} \\ hotS_{21} & hotS_{22} \end{bmatrix} \begin{bmatrix} a_1(f_C) \\ a_2(f_C) \end{bmatrix} + \begin{bmatrix} T_{12} \\ T_{22} \end{bmatrix} e^{j2\varphi(a_1(f_C))} conj(a_2(f_C)) \quad \text{Eq.7}$$

In the above equation the notation conj(.) denotes the conjugate operator. Depending on the DUT, the additional T_{12} and T_{22} terms may or may not be significant. In [7] an example is given where the T_{22} term becomes bigger than the hot S_{22} term. Many people seem to have a problem with an intuitive interpretation of these T terms that are associated with the conjugate of $a_2(f_C)$. There are many ways to explain this phenomenon. One way is to consider the "stability hot S-parameters" of equation 5 and let f_S approach f_C, as illustrated in figure 6. The b_2-wave and the b_1-wave will under these circumstances both have three terms near the frequency f_C: a term at a frequency f_C, a direct reflection term at a frequency f_S and a third term that is a mixing product that appears at a frequency ($2f_C$-f_S). This is actually one of the terms that is neglected for a "stability hot S-parameter" analysis. If f_S approaches f_C, however, the frequency of this mixing product at ($2f_C$-f_S) will get arbitrarily close to f_C and can not be neglected. As can be derived from mixer theory the following linear relationships hold [7].

$$b_1(f_C) = hotS_{11}.a_1(f_C) \quad \text{Eq.8}$$

$$b_1(f_S) = hotS_{12}.a_2(f_S) \quad \text{Eq.9}$$

$$b_2(f_C) = hotS_{21}.a_1(f_C) \quad \text{Eq.10}$$

$$b_2(f_S) = hotS_{22}.a_2(f_S) \quad \text{Eq.11}$$

$$b_1(2f_C - f_S) = T_{12}.e^{j2\varphi(a_1(f_C))}.conj(a_2(f_S)) \quad \text{Eq.12}$$

$$b_2(2f_C - f_S) = T_{22}.e^{j2\varphi(a_1(f_C))}.conj(a_2(f_S)) \quad \text{Eq.13}$$

The conjugate operator is present in equation 12 and in equation 13 because the mixing product at a frequency ($2.f_C$-f_S) is actually a so-called image mixing product. In the limit for f_S going to f_C equation 8 until 13 reduce to equation 7.

V. Conclusions

Hot S-parameters come in many flavors. In order to be useful one needs to understand what kind of hot S-parameters one is dealing with and what their underlying assumptions are.

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Figure 1. “Stability hot S-parameter” forward measurement

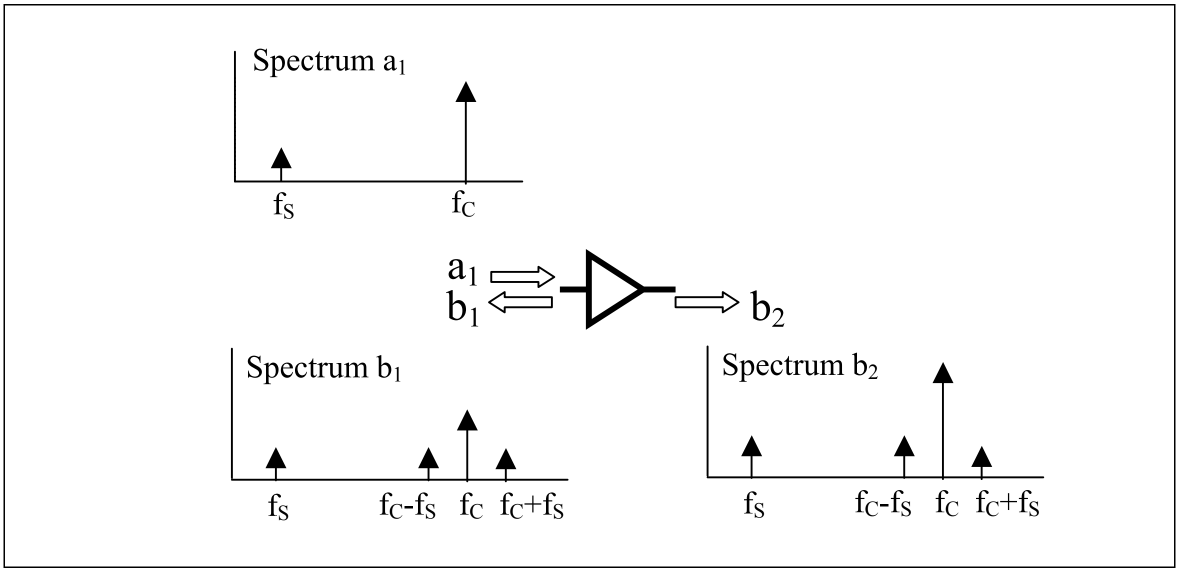

Figure 2. “Stability hot S-parameter” reverse measurement

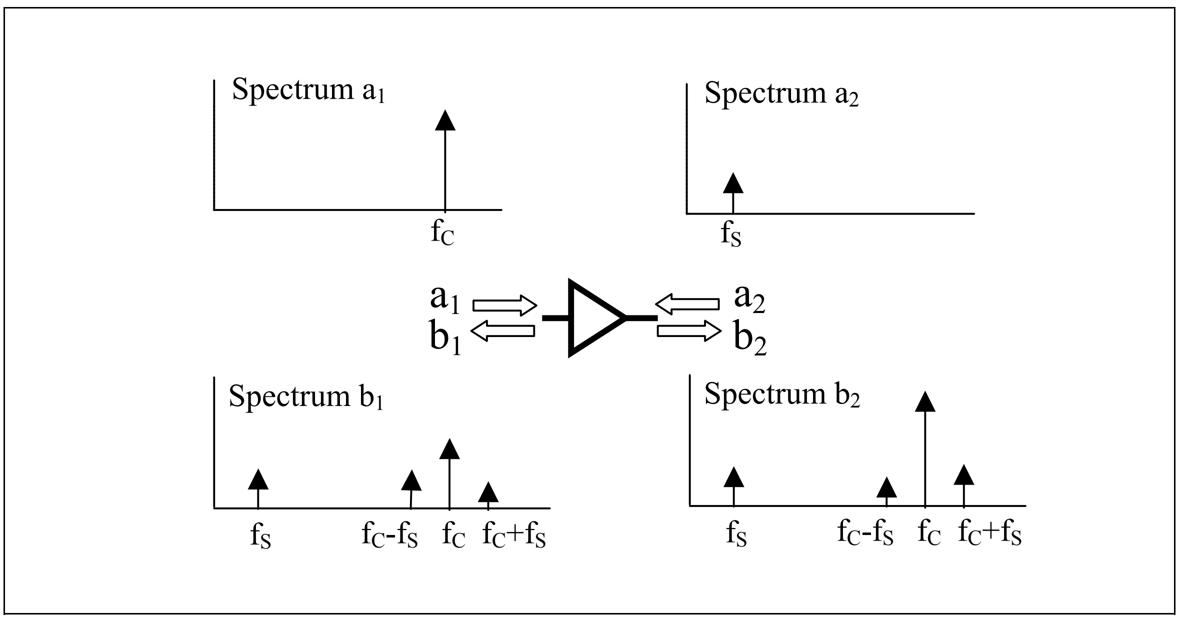

Figure 3. “Hot μ“ stability characteristics as measured by Dunsmore et al.
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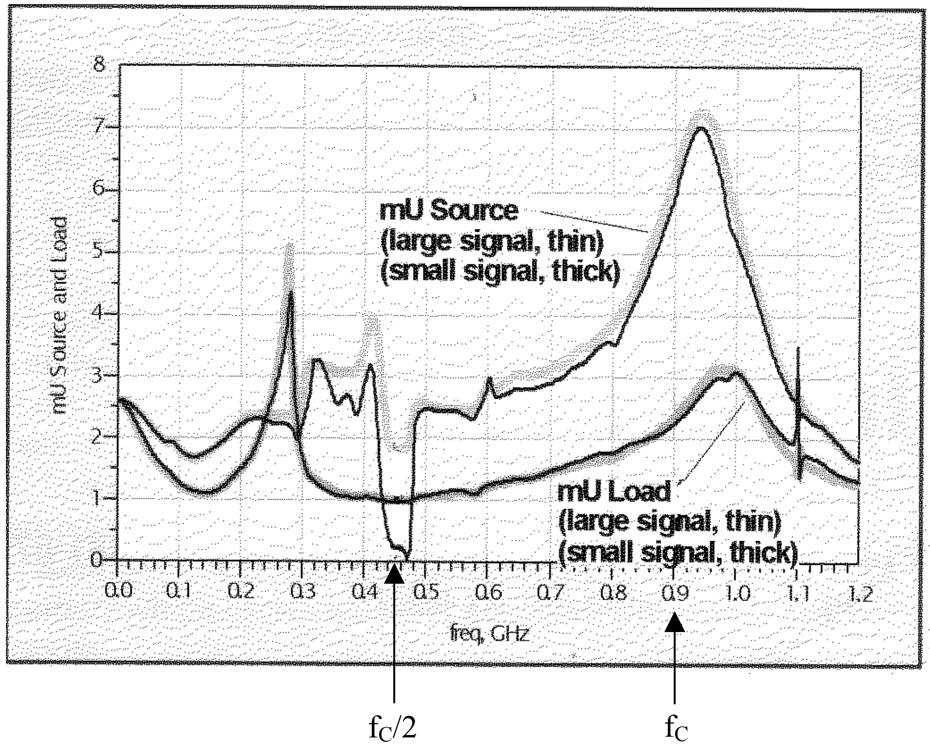

Figure 4. Predicted instability as measured by Dunsmore et al.
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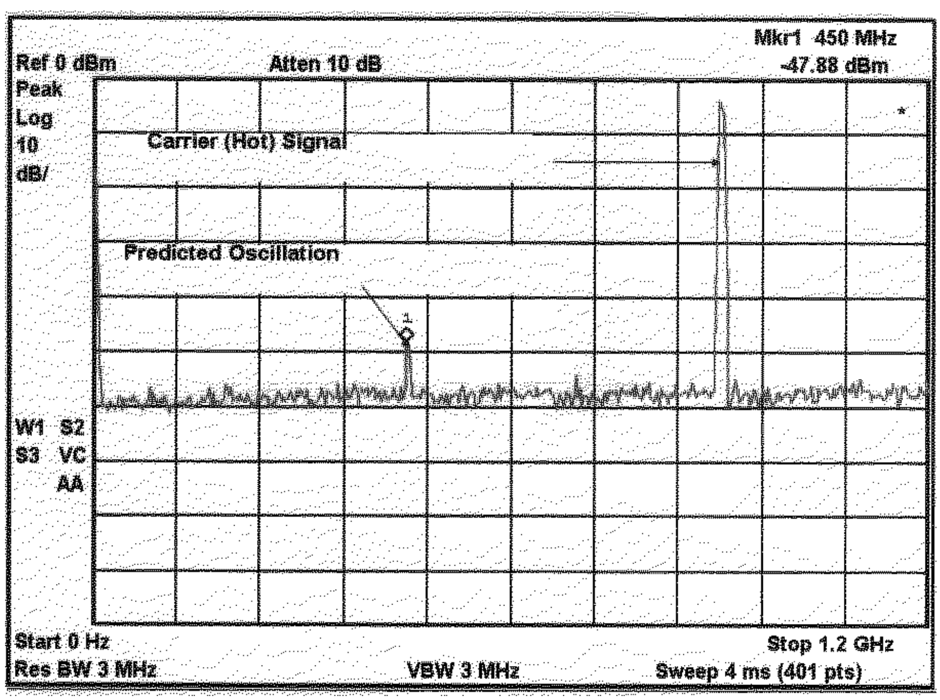

Figure 5. Spectra of the waves for a “distortion hot-S-parameter” description

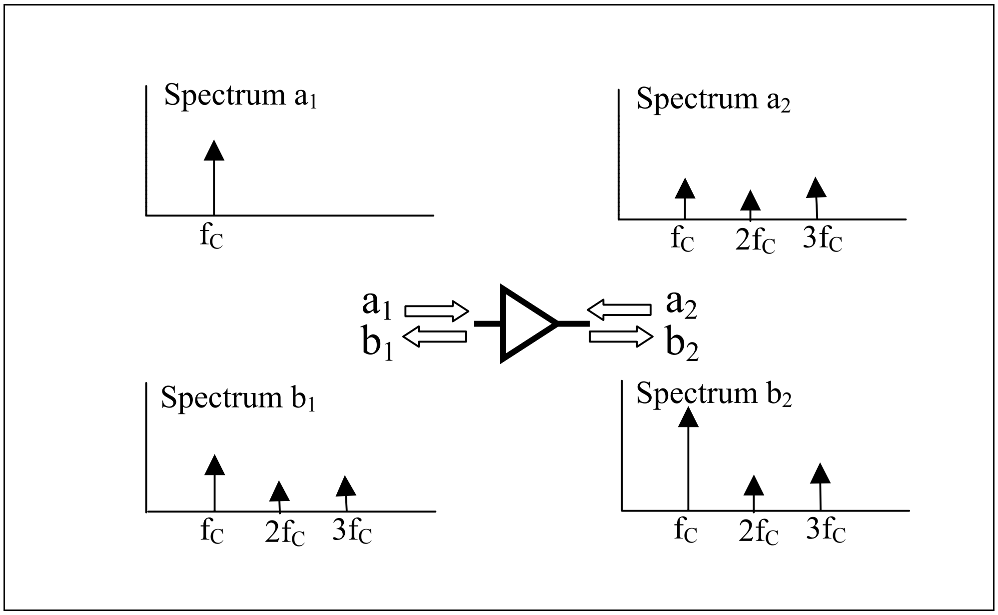

Figure 6. Spectra of the waves in the limit for f_S approaching f_C