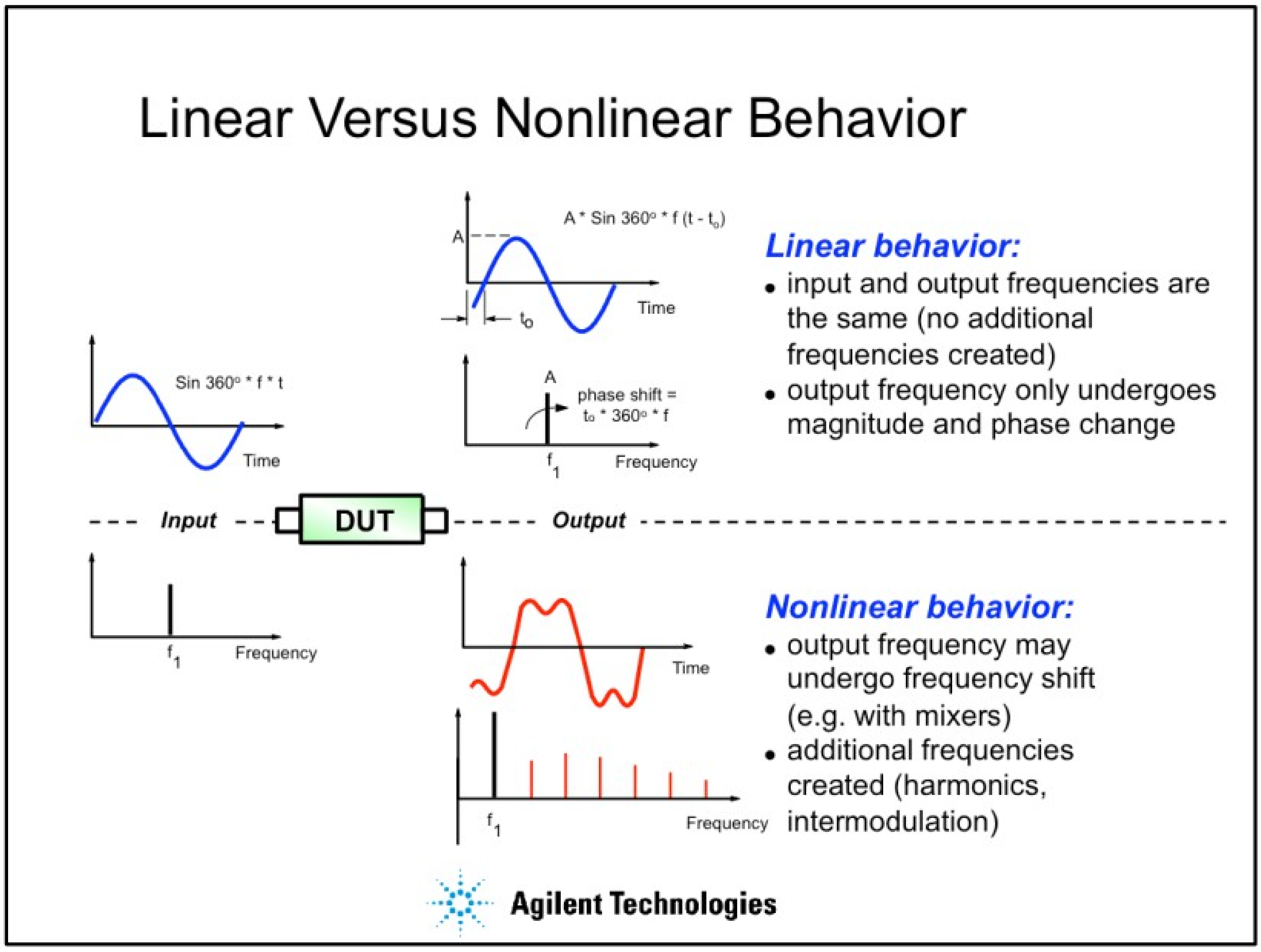
Linear Versus Nonlinear Behavior



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Linear behavior:
- input and output frequencies are the same (no additional frequencies created)
- output frequency *(signal)* only undergoes magnitude and phase change *(Note: due to the presence of reactive elements in the device under test) - true for harmonic signals in steady state. If transient processes take place, then before they end, the signal is quasi-harmonic and additional harmonic components appear.)*

Nonlinear behavior:
- output frequency *(signal)* may undergo frequency shift (e.g. with mixers)
- additional frequencies created (harmonics, intermodulation) *(Note: Due to the presence of elements with non-linear characteristics in the device under test).*

Before we explore linear signal distortion, lets review the differences between linear and nonlinear behavior. Devices that behave linearly only impose magnitude and phase changes on input signals. Any sinusoid appearing at the input will also appear at the output at the same frequency. No new signals are created. When a single sinusoid is passed through a linear network, we don't consider amplitude and phase changes as distortion. However, when a complex, time-varying signal is passed through a linear network, the amplitude and phase shifts can dramatically distort the time-domain waveform. *(which is unacceptable for audio frequency amplifiers)*

Non-linear devices can shift input signals in frequency (a mixer for example) and/or create new signals in the form of harmonics or intermodulation products. Many components that behave linearly under most signal conditions can exhibit nonlinear behavior if driven with a large enough input signal. This is true for both passive devices like filters and even connectors, and active devices like amplifiers

A little explanation.

The harmonic signal is described by the following formula:

$A \cos(\omega_0 t + \varphi_0)$

where A is the signal amplitude,
$\omega_0 = 2\pi f_0$ – circular frequency,
φ_0 is the initial phase.

In this case, A is a constant value, and the signal spectrum consists of a single component with a frequency ω_0 - a monochromatic spectrum.

During transients, the signal becomes quasi-harmonic:

$$s(t) = A(t) \cos [\omega_0 t + \varphi(t)]$$

In contrast to the steady state, the amplitude of the signal A and the initial phase φ depend on time in the section of the transient process. In this case, the signal amplitude A is not constant (as with a harmonic signal), and the signal spectrum becomes complex (with additional harmonic components) depending on the behavior of the function A(t).

With regard to audio frequency amplifiers, direct current amplifiers (DCA) are in a more advantageous position.

The reason for the additional transients is often the inductances included at the output of the amplifier to ensure stable operation. These inductances form a series oscillatory circuit with a reactive load in the form of a capacitance reaching in some cases 8 μF. Therefore, it is advisable, if possible, to develop amplifiers that do not need to stabilize their operation with the help of inductance.

A few words about the signal propagation time (time Propagation Delay). In DC amplifiers, the group delay (GDT) of the signal has a horizontal section from infra-low frequencies and covers the entire audio range. It is very important that this section is not less than 300 kHz. Above this frequency, the group delay should have a smooth decay to zero, a slight increase in the group delay is acceptable. Significant group delay rises contribute to the growth of high-speed distortions (distortions that occur when the frequency or amplitude of the signal changes). The easiest way to measure them is by the compensation method using test signals in the form of signals with a frequency of 10 kHz (sine bursts or triangular).

On the horizontal sections of the Group Delay, its value coincides in magnitude with the value of tPD.

The value of vector errors a for a sinusoidal signal is calculated by the formula:

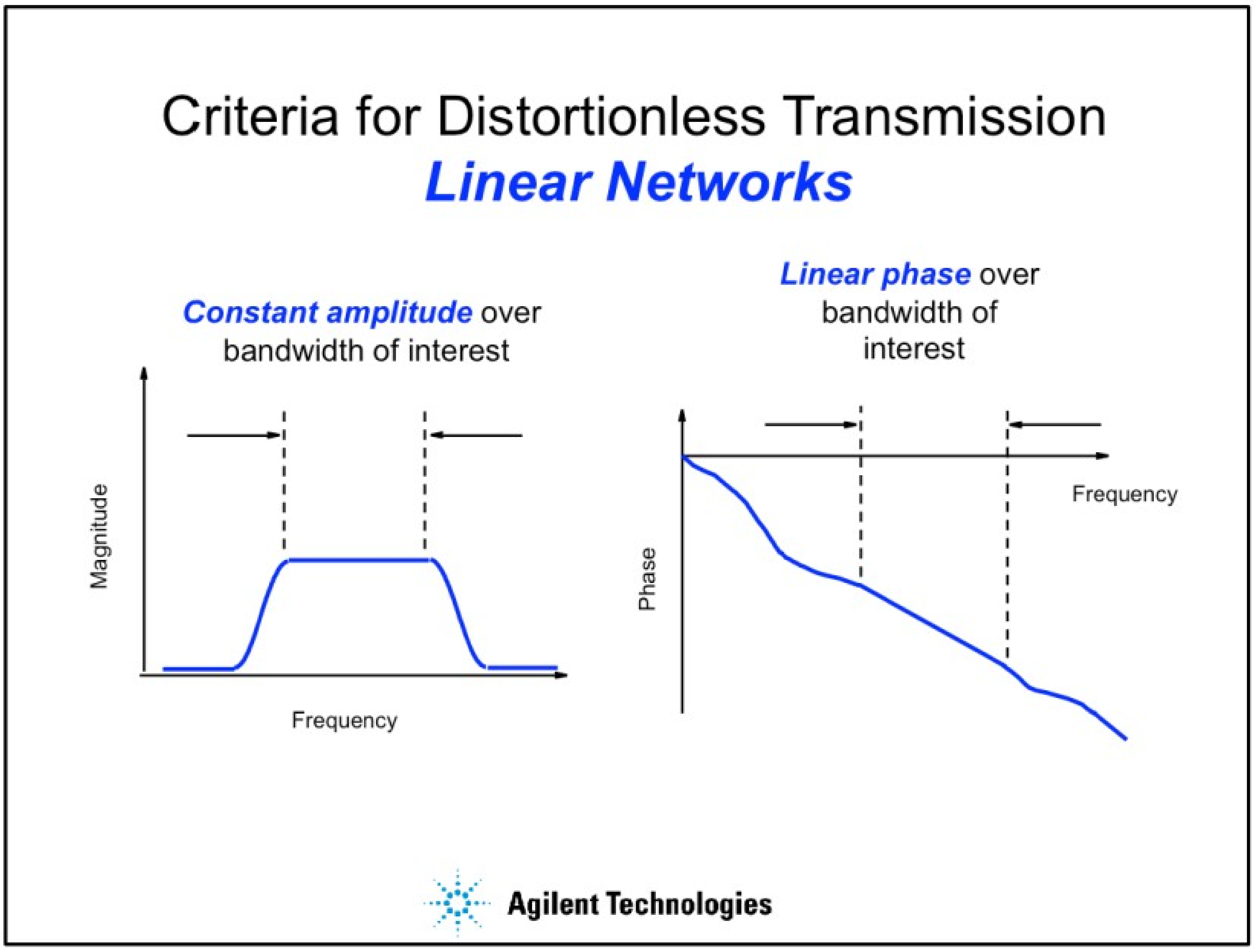
$$a = 2\pi A * tPD/T$$

where
T - is the signal period, μs;
A - is the amplitude of the signal at the output of the amplifier, V:
tPD – time propagation delay, μs

*The criterion for performing the SWDT test (D.Hafler) is a vector error of no more than -60 dB at the highest frequencies of the audio range, and no less than -70 dB in the rest of the range. This requirement for a frequency of 20 kHz corresponds to tPD = T/1000*2π = 50000/6280 = 8 ns.*

However, as practice shows, in some cases it is possible to obtain quite good results in terms of sound quality with tPD not exceeding 100...120 ns (depending on the group delay behavior above 300 kHz) and without the need to use an inductance at the amplifier output.

Literature:
Operational Amplifiers by Jiri Dostal_1993



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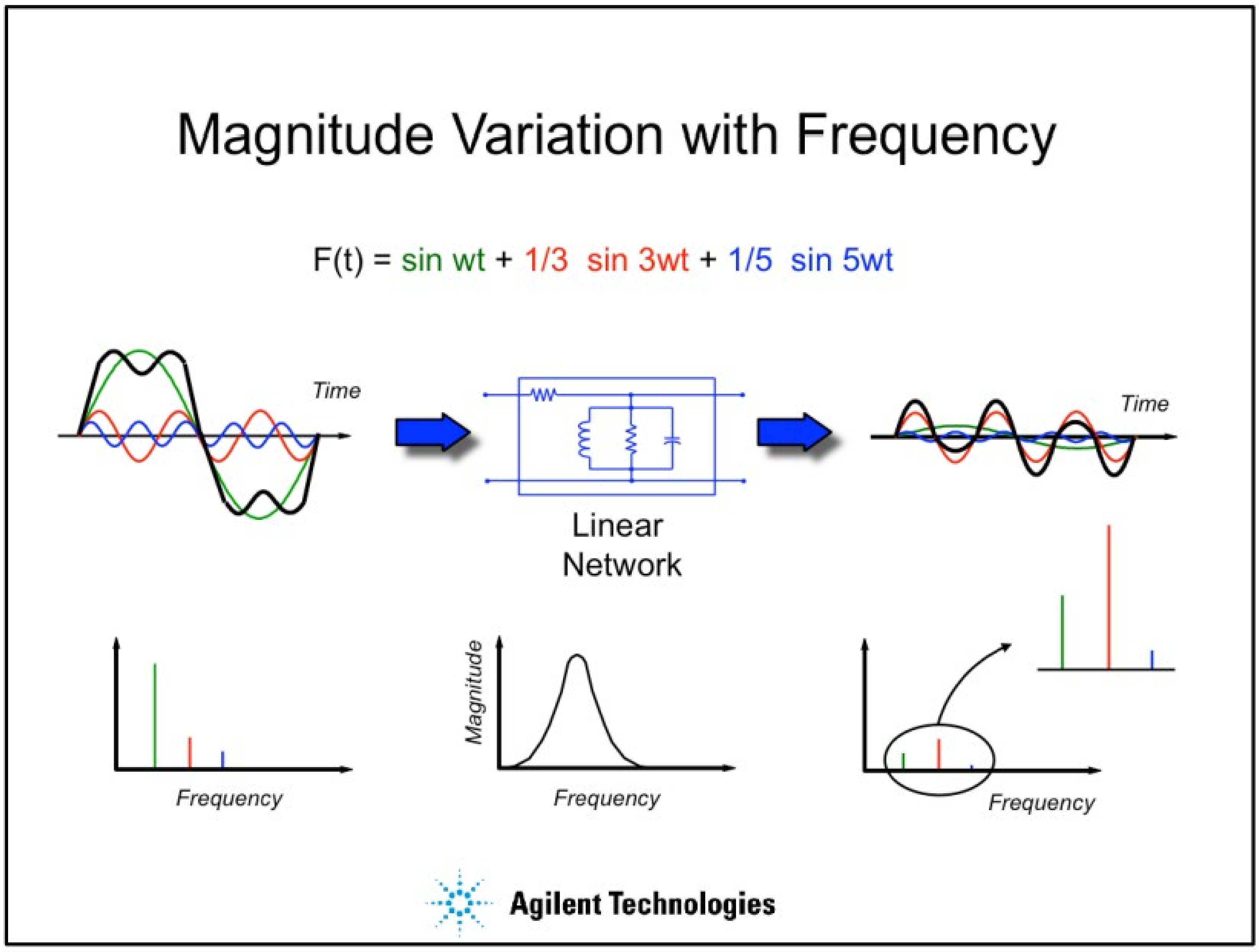
Criteria for Distortionless Transmission
Linear Networks

Now lets examine how linear networks can cause signal distortion. There are three criteria that must be satisfied for linear distortionless transmission. First, the amplitude (magnitude) response of the device or system must be flat over the bandwidth of interest. This means all frequencies within the bandwidth will be attenuated identically. Second, the phase response must be linear over the bandwidth of interest. And last, the device must exhibit a "minimum-phase response", which means that at 0 Hz (DC), there is 0° phase shift (0° ± n*180° is okay if we don't mind an inverted signal). How can magnitude and phase distortion occur? The following two examples will illustrate how both magnitude and phase responses can introduce linear signal distortion.

Note. the phase must be either 0º or 180º for the inverted option. Taking into account psychoacoustics, the linear section of the phase should be from DC to 300 kHz (taking into account the correct transmission of 18 harmonics)



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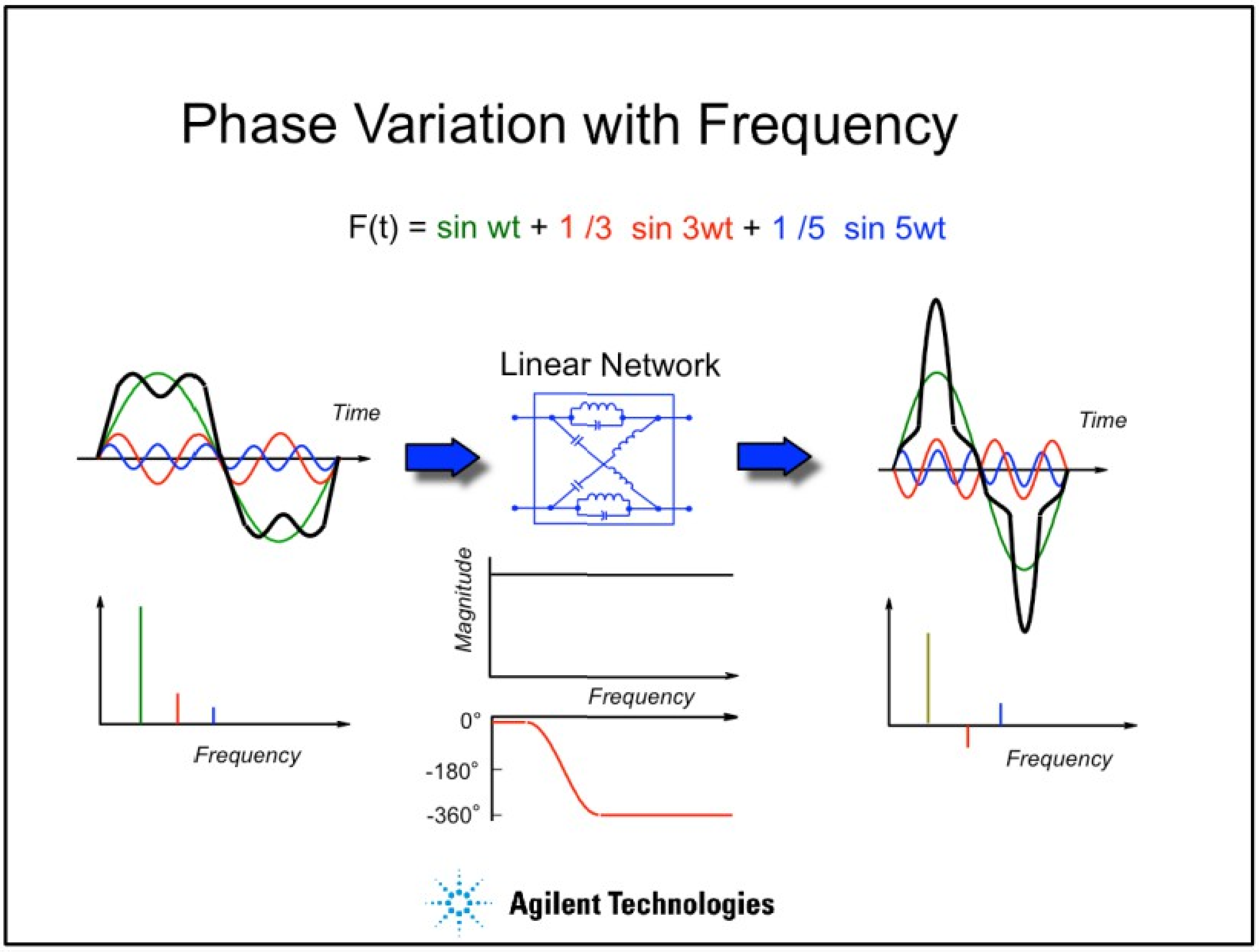
Magnitude Variation with Frequency

Here is an example of a square wave (consisting of three sinusoids) applied to a bandpass filter. The filter imposes a non-uniform amplitude change to each frequency component. Even though no phase changes are introduced, the frequency components no longer sum to a square wave at the output. The square wave is now severely distorted, having become more sinusoidal in nature.

***Note.** The parallel circuit is tuned to the 3rd harmonic, while the 1st and 5th harmonics are attenuated.*



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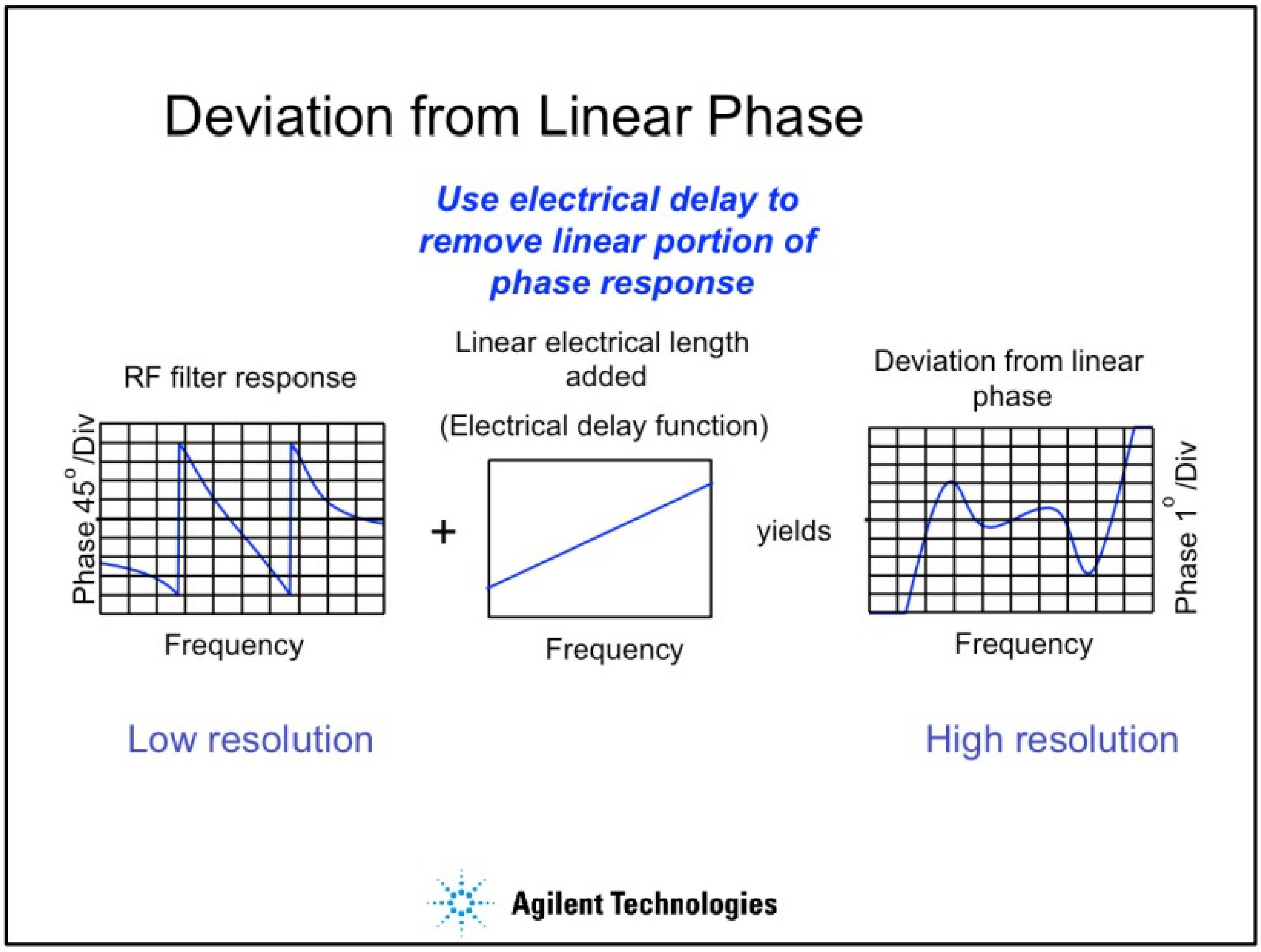
Phase Variation with Frequency

Let's apply the same square wave to another filter. Here, the third harmonic undergoes a 180° phase shift, but the other components are not phase shifted. All the amplitudes of the three spectral components remain the same (filters which only affect the phase of signals are called allpass filters). The output is again distorted, appearing very impulsive this time.



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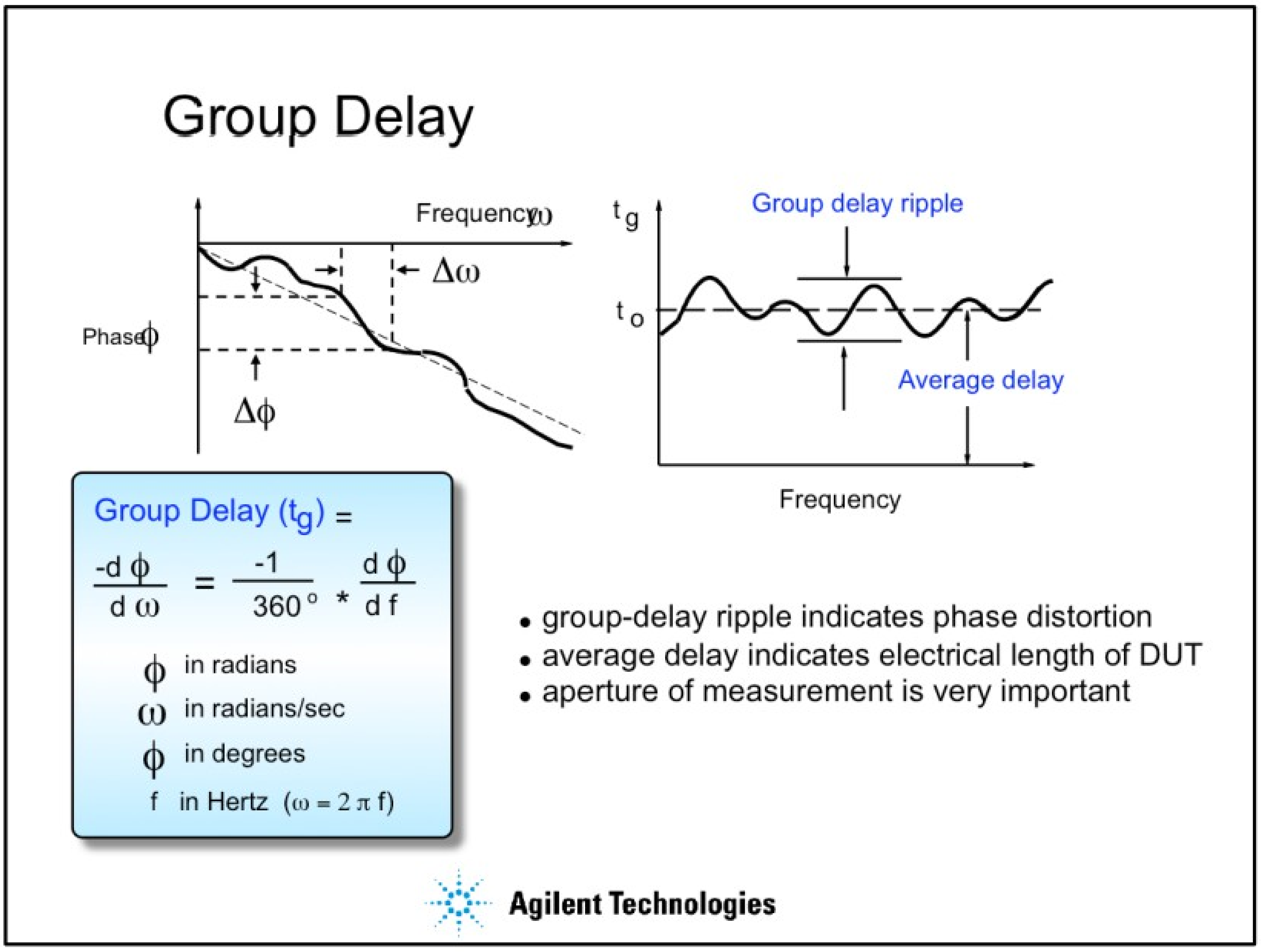
Deviation from Linear Phase
Use electrical delay to remove linear portion of phase response

Now that we know insertion phase versus frequency is a very important characteristic of a component, let's see how we would measure it. Looking at insertion phase directly is usually not very useful. This is because the phase has a negative slope with respect to frequency due to the electrical length of the device (the longer the device, the greater the slope). Since it is only the deviation from linear phase which causes distortion, it is desirable to remove the linear portion of the phase response. This can be accomplished by using the electrical delay feature of the network analyzer to cancel the electrical length *(time Propagation Delay)* of the DUT. This results in a high-resolution display of phase distortion (deviation from linear phase).



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Group Delay

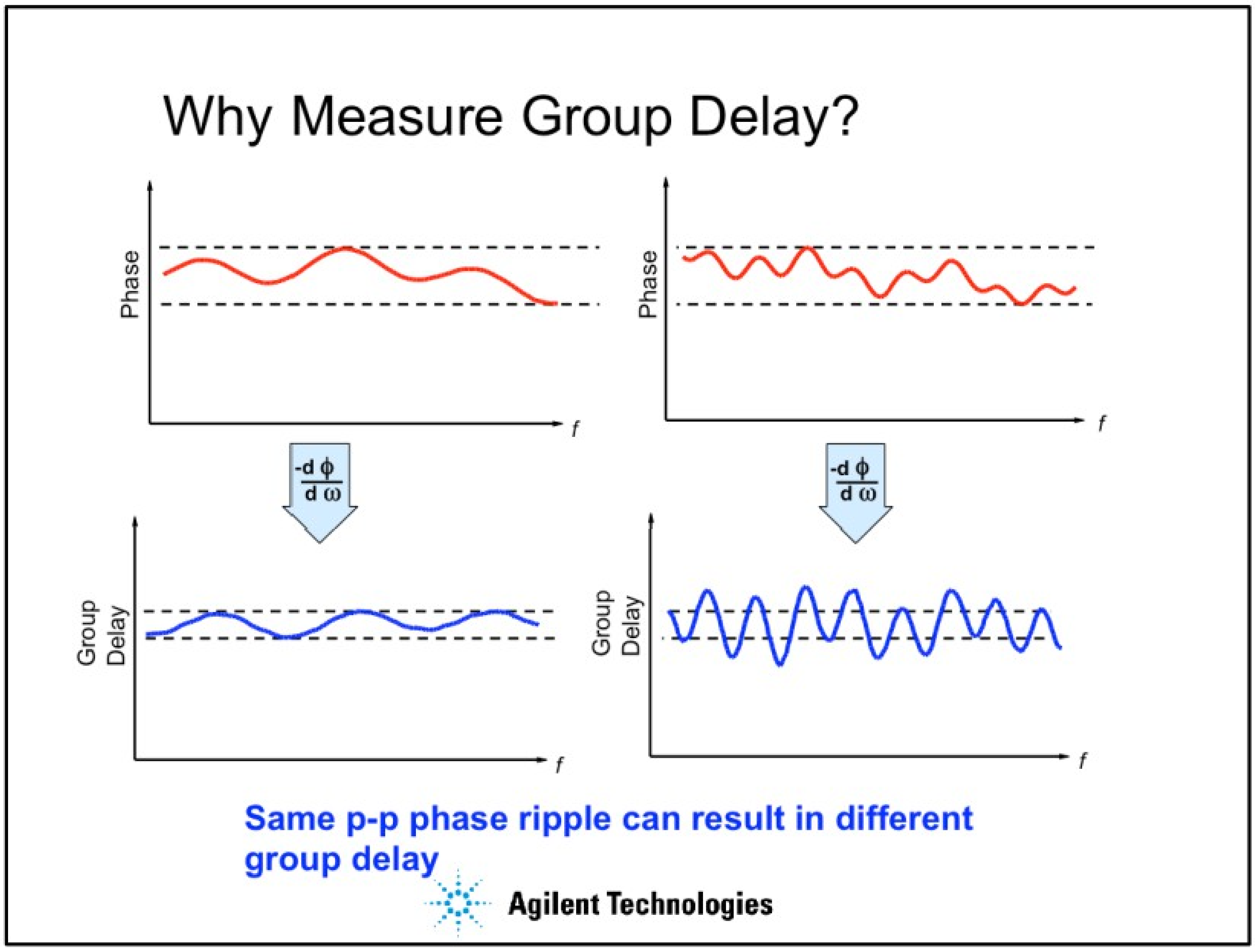
- group-delay ripple indicates phase distortion
- average delay indicates electrical length of DUT
- aperture *(frequency range)* of measurement is very important

Another useful measure of phase distortion is group delay. Group delay is a measure of the transit time of a signal through the device under test, versus frequency. *(Note: On horizontal sections, it is the same as the delay time of the signal at the test frequency).* Group delay is calculated by differentiating the insertion-phase response of the DUT versus frequency. Another way to say this is that group delay is a measure of the slope of the transmission phase response. The linear portion of the phase response is converted to a constant value (representing the average signal-transit time) and deviations from linear phase are transformed into deviations from constant group delay. The variations in group delay cause signal distortion, just as deviations from linear phase cause distortion. Group delay is just another way to look at linear phase distortion.

When specifying or measuring group delay, it is important to quantify the aperture in which the measurement is made. The aperture is defined as the frequency delta *(Δf)*, used in the differentiation process (the denominator in the group-delay formula).

$$\tau_{rp} \approx -\frac{1}{360^\circ} \cdot \frac{\Delta\varphi}{\Delta f}$$

As we widen the aperture, trace noise is reduced but less group-delay resolution is available (we are essentially averaging the phase response over a wider window). As we make the aperture more narrow, trace noise increases but we have more measurement resolution.



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Why Measure Group Delay?
Same p-p phase ripple can result in different group delay

Why are both deviation from linear phase and group delay commonly measured? Depending on the device, both may be important. Specifying a maximum peak-to-peak value of phase ripple is not sufficient to completely characterize a device since the slope of the phase ripple is dependent on the number of ripples which occur over a frequency range of interest. Group delay takes this into account since it is the differentiated phase response. Group delay is often a more easily interpreted indication of phase distortion. *(note. Like in an amplifier Hafler XL-280)*

The plot above shows that the same value of peak-to-peak phase ripple can result in substantially different group delay responses. The response on the right with the larger group-delay variation would cause more signal distortion.