A Study on Feedforward System for IMT-2000

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Abstract : A linear power amplifier is particularly emphasized on the system using a linear modulations, such as 16QAM and QPSK with pulse shaping, because intermodulation distortion which causes adjacent channel interference and co-channel interference is mostly generated in a nonlinear power amplifier. In this paper, parameters of a linearization loop, such as an amplitude imbalance, a phase imbalance and a delay mismatch, are briefly analyzed to get a specific cancellation performance and linearization bandwidth. Experimental results are presented for IMT-2000 frequency band. The center frequency of the feedforward amplifier is 2140 MHz with 60 MHz bandwidth. When the average output power of feedforward amplifier is 20 Watt, the intermodulation cancellation performance is more than 21 dB. In this case, the output power of feedforward amplifier reduced 3.5 dB because of extra delay line loss and coupling loss. The feedforward amplifier efficiency is more than 7.2 % for multicarrier signals, 59 dBc for ACPR.

Key words : Linearization, Feedforward, Delay line, Intermodulation

1. Introduction

The primary goal of any radio system is to transmit and receive information. Most analog first generation cellular systems are limited to speech, but the development of second generation digital systems is allowing both speech and limited data capabilities. Future third generation systems and indeed developed second generation systems are expected to support much higher rates of data transfer, thus enabling wireless multimedia services such as video and the Internet to become a reality. One of the reasons that it is becoming more practical and cost effective to offer such services is that radio frequency power amplifiers, which are inherently nonlinear, can be built to very high specifications and fulfill the requirements of a “linear amplifier.” This has not been possible thus far using traditional techniques because the amplifiers generate distortion in the form of intermodulation and spectral regrowth. Power generated outside of the transmit

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channel, that is not out-of-band emission of -60 dBc, cause interference in adjacent radio channels, while power generated in-band can cause errors in signal vectors and hence, a degradation in demodulation accuracy(Nick Pothecary, 1999), (Rappaport, T, S. 2001).

Several linearization approaches have been developed(Seidel, H. 1971), (Sundstrom, L. 1996), (Nagata, Y. 1989). Feedforward linearization(Cavers, James K. 1995) has advantages in linearization bandwidth and cancellation performance over other linearization methods. Since the signals are manipulated by inherently wideband analog technology, it can handle multicarrier signals.

2. Technologies for Nonlinear Compensation

We introduce some techniques for nonlinear compensation of power amplifiers. Most radio communication equipment has a power amplifier, the efficiency of which nearly always needs to be as high as possible. Efficiency is defined as the radio of RF output power to the total power consumed. There is a general property that amplifier efficiency is inversely proportional to amplifier linearity. If you need a high linearity, an amplifier should be operated in class A or AB, which makes the power efficiency quite low. Conversely, if you need high efficiency, an amplifier should be operated near class C, which makes the amplifier very nonlinear. Many nonlinear compensation techniques have been proposed and developed to find an optimal balance between efficiency and linearity (Kenington, P. B. 2000).

2.1 Efficiency

Efficiency, like linearity, is a critical factor in power amplifier design. The efficiency of an amplifier is measure of how effectively DC power is converted to RF power, that is

$$\eta = \frac{P_{out}}{P_{DC}} \tag{1}$$

In a feedforward amplifier there are main and error amplifiers each drawing power from the DC supply, thus the total DC power is

$$P_{DC} = P_{DC,M} + P_{DC,E} \tag{2}$$

Feedforward system efficiency, as shown in Fig. 1, is thus affected by the following factors:

① Coupler insertion losses

② Delay line loss

③ Efficiency of the main amplifier (at maximum average output power)

④ Efficiency of the error amplifier (at peak power)

⑤ Signal peak-to-average ratio

⑥ Radio of the main and error amplifier peak powers (intermodulation performance of the main amplifier and carrier suppression).

The efficiency of a practical feedforward amplifier is dependent on additional factors. For example, the power consumption of other components (digital and analog), such as gain/phase adjustment circuits, detector circuits, low power amplifier stages, loop control circuitry, and the efficiency of any DC/DC conversion. Furthermore, depending on whether cooling fans are an integral part of the feedforward amplifier, it may be necessary to include their power consumption in any efficiency calculation.

In Fig. 1 the feedforward efficiency is higher when a GaAs amplifier is used as the error amplifier rather than a bipolar amplifier. The typical efficiencies of bipolar and MOSFET main amplifier are comparable, for example 15 %, and gives an overall feedforward efficiency of 8.4 % and 5.4 % (GaAs and bipolar amplifiers, respectively). The efficiency of Class AB feedforward amplifiers is thus in general relatively low (5 % to 10 %), and therefore it is always desirable to minimize the RF output power to reduce power consumption and heat dissipation(Pothecary, Nick 1999).

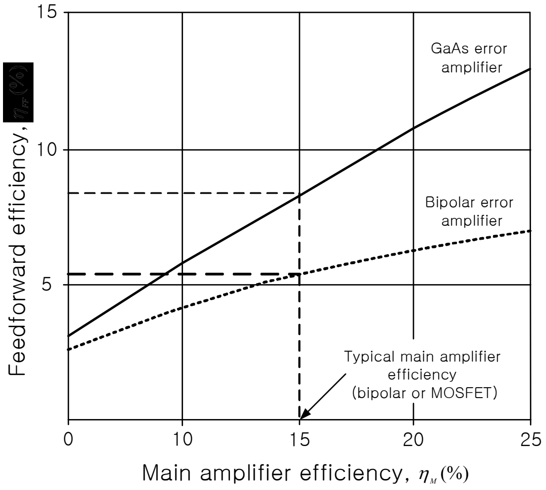


Fig. 1 Feedforward efficiency-10 dB signal peak-to-average ratio

2.2 Feedforward Amplifier

The very wide bandwidths (10~100 MHz) required in multicarrier applications can render feedback and DSP impractical. In such cases, the feedforward technique can be used to reduce distortion by 20~40 dB. A feedforward amplifier, as shown in Fig. 2, consists of two amplifier (the main and error amplifiers), directional couplers, delay lines, and loop control network. The directional couplers are used for power splitting/combining, and the delay lines ensure operation over a wide bandwidth. Loop control networks, which consist of amplitude and phase shifting networks, maintain signal and distortion cancellation within the various feedforward loops (Pothecary, Nick 1999).

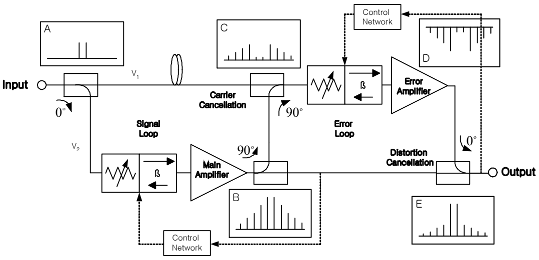


Fig. 2 Configuration of the feedforward amplifier

The input signal is first split into two paths, with one path going to the high power main amplifier, while the other signal path goes to a delay line. The output signal from the main amplifier contains both the desired signal and distortion. This signal is sampled and scaled using attenuators before being combined with the delayed portion of the input signal, which is regarded as distortion free. The resulting "error signal" ideally contains only the distortion components in the carrier cancellation port. The error signal is then amplified by the low power high linearity error amplifier, and then combined with a delayed version of the main amplifier output. This second combination ideally cancels the distortion components in the distortion cancellation port while leaving the desired signal unaltered(Raab, F. H. 2002).

2.3 The Gain and Phase Accuracy

Perfect signal cancellation implies that the resultant vector, that is, the suppressed signal, has a magnitude of -∞ dB relative to the unsuppressed signal. For practical purpose, however, it is of interest to know how closely signals need to be matched for a certain finite suppression.

Fig. 3 shows the vector addition of two voltages: a reference signal with amplitude 1 and phase 0°, and a nonideal canceling signal with amplitude $1+\delta\mathbf{A}$ and phase $180°+\phi$. Using the cosine rule, the magnitude of the resultant vector **r**, which has the same frequency as the canceling signals, can be calculated from

$$r^2 = (1+\delta A)^2 + 1 - 2(1+\delta A)\cdot\cos(\phi) \qquad (3)$$

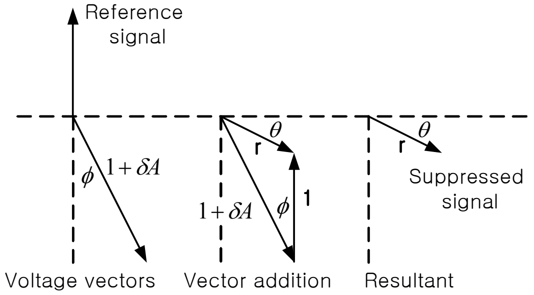


Fig. 3 Signal cancellation-vector addition

The level of the canceled or suppressed signal is thus a function of two variables, the amplitude mismatch δA and the phase mismatch ϕ. Rewriting (3) in terms of the suppression CP (dB) and amplitude mismatch △A (dB) gives

$$CP = 10\log\left(\left|\left(10^{\frac{\Delta A(dB)}{10}}\right)^2 + 1 - 2\cdot 10^{\frac{\Delta A(dB)}{10}}\cdot\cos(\phi)\right|\right)$$

(4)

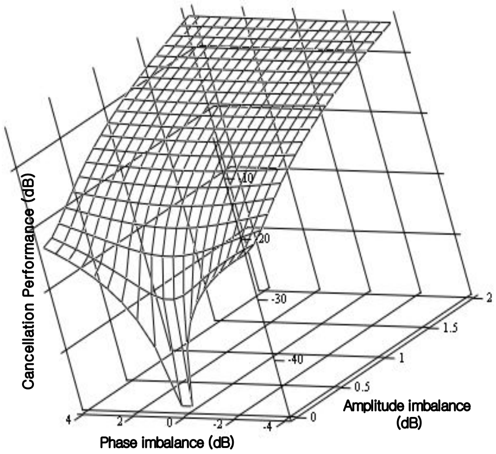


Fig. 4 Loop suppression and gain/phase matching requirement

The cancellation performance of an amplitude and phase is graphically shown in Fig. 4.

Successful isolation of an error signal and the removal of distortion components depend upon precise cancellation over a band of frequencies. For a 30 dB cancellation depth, as shown in Fig. 5, the amplitudes must be matched with 0.22 dB and the phases with 1.2°. For manufactured equipment, realistic values of distortion cancellation are around 20~30 dB.

Assuming that the signal in each path of a linearization loop is an equal amplitude with 180° phase difference in order to consider the effects of a delay mismatch on the cancellation performance.

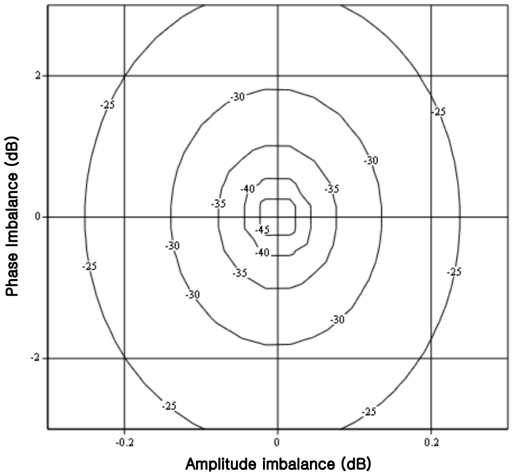


Fig. 5 The gain and phase accuracy

Let $V_1=\cos(\omega_0 t+\theta_1)$, $V_2=-\cos(\omega_0 t+\theta_2)$, where V_1 is the signal in the upper path, and V_2 is the signal in low path, as shown in Fig. 2. Then V_{out}, output signal of a linearization loop is V_1+V_2, a normalized average power of V_{out} can be written as

$$P_{vout,avg}=1-\cos(\theta_1-\theta_2) \tag{5}$$

where $P_{vout,\ avg}$ is a normalized average power of V_{out}, and θ_1, θ_2 are an electrical length of each path of a linearization loop. From eq. (5) we can get an infinite cancellation performance if an electrical length of each path is the same. However, in practice, the amounts of time delay of each path are same at a specific frequency which is the center frequency of a linearization loop. Therefore, we can get a required cancellation performance with only certain bandwidth. The cancellation performance of a linearization loop including the effect of a delay mismatch (without amplitude and phase imbalance) can be written as

$$CP=10\log(1-\cos(\theta_1-\theta_2))+3 \tag{6}$$

Eq. (6) can be represented by a function of wavelength of the difference in wavelength between two paths to cause a delay mismatch.

$$CP=10\log\left(1-\cos\left(2\pi\left(\frac{\lambda_{err}}{\lambda_0}\right)\left(1-\frac{f}{f_0}\right)\right)\right)+3$$

(7)

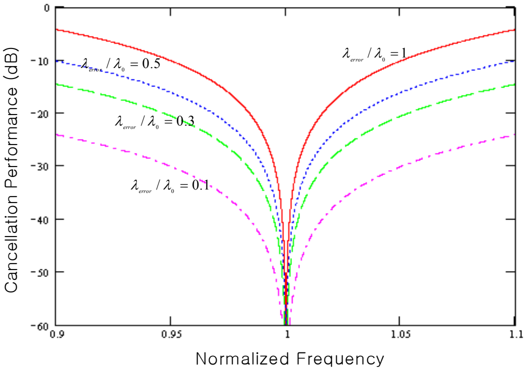


Fig. 6 Effect of a delay mismatch on the cancellation performance of a linearization loop

where f_0 is a center frequency of a linearization loop, λ_0 is a wavelength at the center frequency, and λ_{err} is the difference between two paths at f_0. Fig. 6 shows the effects of a delay mismatch on the cancellation performance and linearization bandwidth of a linearization loop.

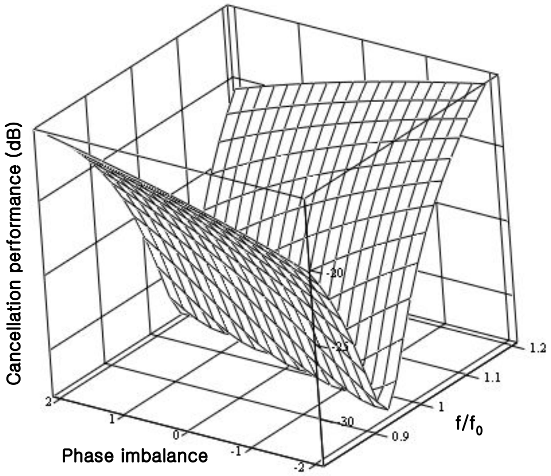


Fig. 7 Cancellation performance of linearization loop for △A=0.1 dB, $\lambda_{err}/\lambda_0=0.1$

From eq. (4) and eq. (7), an amplitude imbalance, a phase imbalance and a delay mismatch exist in a linearization loop, then the cancellation performance of a linearization loop can be written as

$$CP = 10\log\left(1+\left(10^{\frac{\Delta A(dB)}{10}}\right)^2-2\cdot 10^{\frac{\Delta A(dB)}{10}}\cdot\cos\left(2\pi\left(\frac{\lambda_{err}}{\lambda_0}\right)\left(1-\frac{f}{f_0}\right)+\phi\right)\right)$$

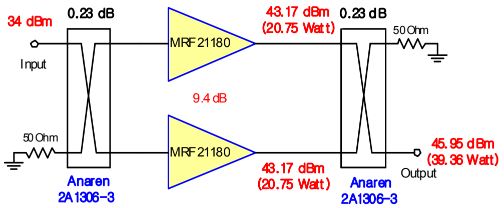
(8)

Fig. 7 shows the effects of an amplitude imbalance, phase imbalance and a delay mismatch on the cancellation performance of a linearization loop.

2.4 Power Combiners

Whether to use a number of smaller power amplifiers versus a single larger power amplifier is one of the most basic decisions in selection of an architecture(Cripps, S. C. 1999). Even when larger devices are available, smaller devices often offer higher gain, a lower matching Q factor (wider bandwidth), better phase linearity, and lower cost. Heat dissipation is more readily accomplished with a number of small devices, and a soft-failure mode become possible. On the other hand, the increase in parts count, assembly time, and physical size are significant disadvantages to the use of multiple, smaller devices.

In the corporate architecture, power in Fig. 8 is split and combined. Hybrid combiners isolate the two power amplifiers from each other and allow one to continue operating if the other fails. Quadrature combiners insert a 90° phase shift at the input of one power amplifier and a 90° phase shift at the output of the other. This provides a constant input impedance, cancellation of odd harmonics, and cancellation of backward-IMD(IMD resulting from a signal entering the output port). In addition the effect of load impedance upon the system output is greatly reduced.



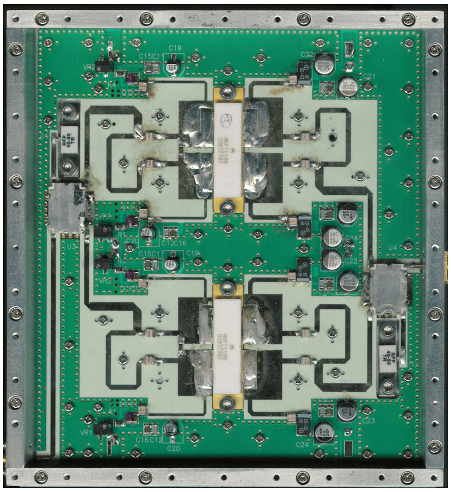


Fig. 8 Balanced amplifier with coupler

3. Feedforward Linearization System Design and Experiment Result

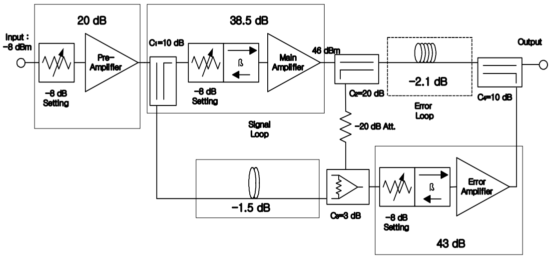


Fig. 9 The detailed block diagram of a Feedforward system

The main amplifier employed MRF-21180 as a final balanced amplifier in Fig. 8. The center frequency of the main amplifier is 2140 MHz with 60 MHz bandwidth. The total power gain of the main amplifier is 38.5 dB with ±0.1 dB gain flatness and the phase variation is within 90° over the operating bandwidth, as shown in Fig. 10. The average output power of the main amplifier is 46 dBm (40 Watt). The frequency bandwidth of error amplifier is 60 MHz to suppress the distortion component. The gain of the error amplifier is 43 dB with ±0.3 dB gain flatness, as shown in Fig. 11.

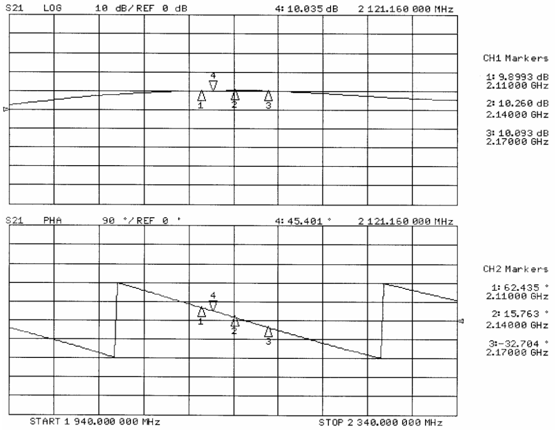


Fig. 10 The gain characteristics of the main amplifier

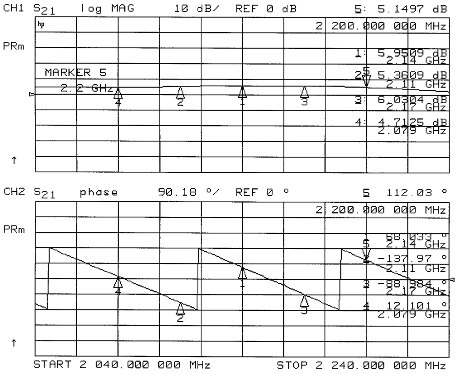


Fig. 11 The gain characteristics of the error amplifier

The 20 dB directional coupler is used for the first linearization loop with coupler 2 shown in Fig. 9, and 10 dB directional coupler for second linearization loop with coupler 4 shown in Fig. 9. The substraction circuit used 3 dB Wilkinson combiner.

A reflection type hybrid phase shifter using varactor diode is used. The phase shifter has 60° of the adjustable phase control range by employing 3 dB hybrid coupler. The voltage variable attenuator manufactured by Mini-Circuits (RVA-2500) is used, and the attenuation range of the voltage variable attenuator is about 10 dB.

The 2-tone intermodulation characteristic of main amplifier is shown in Fig. 12. Fig. 12 shows that the intermodulation characteristic of the main amplifier is 40 dBc. The cancellation performance of the first linearization loop is represented in Fig. 13. The 2-tone intermodulation characteristic of the implemented 20 Watt linear power amplifier, as shown in Fig. 14, is about -61 dBc and intermodulation cancellation performance is more than 21 dB. In this case, output power is reduced 3.5 dB because of extra delay line loss and coupling loss.

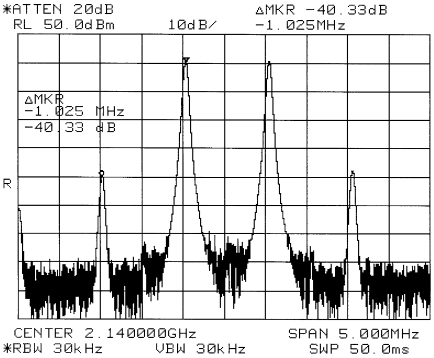


Fig. 12 2-tone intermodulation characteristic of the main amplifier before linearization.

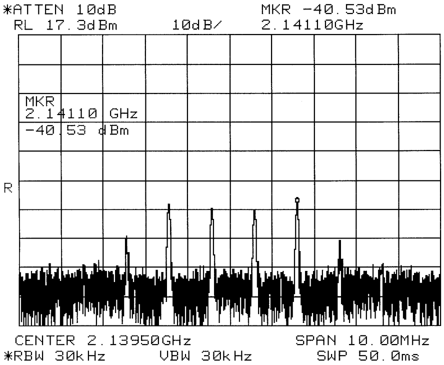


Fig. 13 Subtracter output

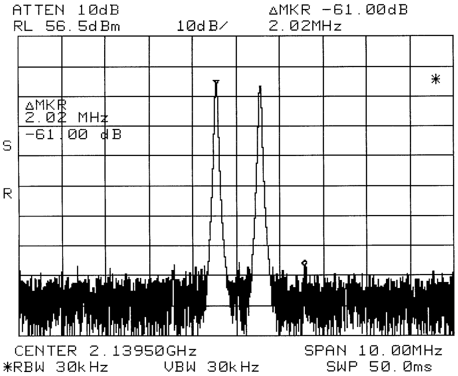


Fig. 14 2-tone intermodulation characteristic of the feedforward amplifier after linearization.

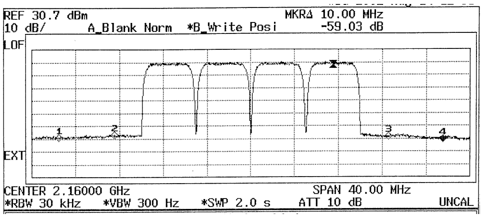


Fig. 15 ACPR of the feedforward amplifier after linearization.

The outputs of the main and error amplifiers are combined in a directional coupler that both isolates the power amplifiers from each other and provides resistive input impedances. For a 20 dB coupling ratio with coupler 2, 80 % of the power from the main power amplifier reaches the output. For a 10 dB coupling ratio with coupler 4, only 10 % of the power from the error amplifier reaches the load, thus the error amplifier must produce ten times the power of the distortion in main amplifier. The peak-to-average ratio of the error signal is often much higher than that of the desired signal, making amplification of the error signal inherently much less efficient than that of the main signal. As a result, the power consumed by the error amplifier can be a significant fraction of that of the main amplifier. In addition, it may be necessary to operate one or both amplifiers well into backoff to improve linearity. The overall average efficiency of a feedforward amplifier is, therefore, 7.2 % for multicarrier signals.

4. Conclusion

The feedforward linearization techniques are effective in intermodulation distortion cancellation. Parameters, an amplitude imbalance, a phase imbalance and a delay line mismatch, of a feedforward amplifier are briefly analyzed to get a specific cancellation performance and linearization bandwidth. The experimental results demonstrate that this technique is effective. Linear amplifiers are thus effectively transparent to the modulation format and number of carriers. Furthermore, using linearization technique, linear amplifiers can operate with low levels of distortion over the wide bandwidths that are necessary to support high data rate services such as the Internet and wireless multimedia, which is based upon wideband code division multiple access (WCDMA). Some key factors affecting overall system performance, such as frequency bandwidth, stability vs. temperature, and reliability should be investigated further.

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