
Vol. 50 • No. 4
April 2007
Microwave Journal
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A FEED-FORWARD AMPLIFIER USING AN EQUAL GROUP-DELAY SIGNAL CANCELLATION TECHNIQUE

In this article, new signal cancellers that can match the out-of-phase and group delay of two signal paths simultaneously are proposed. The simultaneous matching of the out-of-phase and group-delay time between two paths can permit broadband signal cancellation. A feed-forward linear power amplifier that uses the proposed signal cancellers was fabricated for the IMT-2000 base station transmitting band. The main signal cancellation (first) loop of the fabricated feed-forward amplifier cancels the input signal by more than 26.3 dB and the intermodulation distortion (IMD) signal cancellation (second) loop cancels the IMD signal by more than 15.2 dB over a 200 MHz bandwidth. In the two-tone signals amplification process, the C/I ratio of the amplifier was improved by 21.2 dB, where the two tones were 2115 and 2165 MHz (Δf = 50 MHz), respectively.

Modern wireless communication systems utilize digital modulation techniques employing linear complex coding schemes to maximize the channel throughput available capability. Also, a broader channel bandwidth is used for more data transmission than before. In addition, as various communication services, such as cellular phone (IS-95), personal communication service (PCS), IMT-2000 and mobile Internet are provided, the service frequency bandwidth is also broadened. These linear modulation schemes increase the peak-to-average ratio of the RF signal and the envelope variation of the signal is changed seriously.

A power amplifier is usually operated in the saturation region for maximum efficiency and high output power. As the power amplifier operates close to saturation, its linearity degradation becomes significant, due to the nonlinear characteristic of the power amplifier. Therefore, to the power amplifier designer, high linearity and high efficiency are critical issues. Hence, a compromise between power efficiency and linearity must be considered, otherwise a linearization technique to overcome the nonlinearity of the power amplifier is the only solution.

Various linearization methods, such as feed-forward, feedback, predistortion, LINC (linear amplification with nonlinear components), CALLUM (combined analog locked-

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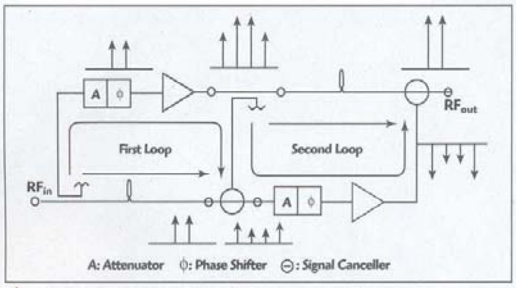
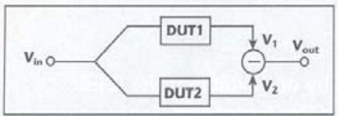
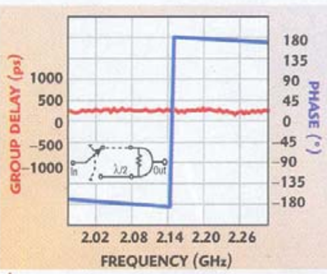
loop universal modulator) and EER (envelope elimination and restoration) have been reported.[1,2] The analog predistortion method is conceptually the simplest form of linearization for an RF power amplifier, but its intermodulation reducing effect is not as good as for the feed-forward method. Digital predistortion shows good linearization results, but has a limited linearization frequency bandwidth because of the memory effect.[3–6] Among the numerous amplifier linearization techniques, feed-forward linearization has been extensively used in base station amplifiers, because of its intrinsic advantages of providing high linearity and a broadband linearizing bandwidth.[1–3] Although the feed-forward method can linearize over a broader band than any other linearizing methods, the bandwidth, for more than 20 dB reduction of the IMD components, is limited in practice. Previously, several broadband feed-forward applications, having a delay line phase equalizer or a multi-stage hybrid, have been presented.[7,8] However, the phase equalizer has difficulty in matching the phase characteristics of the power amplifier, because the amplifier consists of several transistor stages and its phase characteristics change according to the operating conditions and case-by-case differences. The multi-stage 3 dB hybrid method uses only its broadband characteristics. The previous approaches focus on the amplitude and out-of-phase matching between the two paths of the feed-forward loop, but ignore the group-delay matching. In this article, new signal cancellers that match the broadband out-of-phase and group-delay characteristic simultaneously between the two paths of the feed-forward loop are proposed. The proposed cancellers provide broadband signal cancellation in the feed-forward loop.



▲ *Fig. 1 Block diagram of a feed-forward amplifier.*



▲ *Fig. 2 Equivalent loop of the feed-forward amplifier.*

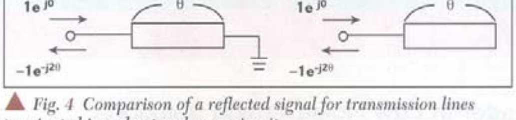


▲ *Fig. 3 Phase and group delay transmission characteristics of a Wilkinson canceller.*

THEORY OF OPERATION OF A LINEARIZER

Analysis of a Feed-forward Equivalent Loop

Basically, a feed-forward amplifier consists of two signal cancellation loops that have the same operating principle and the same frequency components are cancelled in each loop. ***Figure 1*** shows the block diagram of a feed-forward amplifier, where the principle of operation is well illustrated for a two-tone spectrum. ***Figure 2*** shows an equivalent loop of the feed-forward amplifier for amplitude analysis, and phase and group-delay matching. Assuming that the signal in each path of the equivalent loop is sinusoidal, then the signal in the two paths can be written as



▲ *Fig. 4 Comparison of a reflected signal for transmission lines terminated in a short and open circuit.*

$$V_1 = V_{1m}\cos(\omega_0 t - \phi) \quad (1)$$

$$V_2 = V_{2m}\cos(\omega_0 t - \phi) \quad (2)$$

where

$V_{1m} = V_{2m} + \Delta V$, $\theta = \phi + \pi + \Delta\phi$

If there are amplitude, phase and delay mismatchings between the two paths, then the cancellation performance (CP) can be written as[9]

$$CP = 10\log\left[1 + \alpha^2 - 2\alpha\cos\left\{2\pi\left(\frac{\lambda_{err}}{\lambda_0}\right)\left(1 - \frac{f}{f_0}\right) \pm \Delta\phi\right\}\right] \quad (3)$$

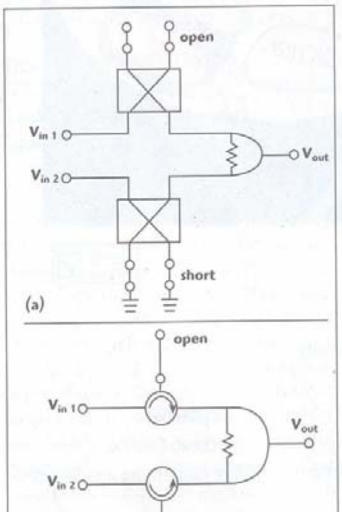
where f_0 and λ_0 are the center frequency and wavelength. α, $\Delta\phi$ and λ_{err} are the amplitude, phase and group-delay mismatching parameter, respectively. The amplitude and the phase matchings are important for single frequency component cancellation, but the group-delay time matching is also an important parameter for broadband signal cancellation. ***Figure 3*** is a good example of the importance of group-delay matching in the feed-forward loop, where the characteristics of a Wilkinson canceller, which is one of the usual signal cancellers, are shown. The transmission phase and group-delay characteristics of a Wilkinson canceller, with one input port connected to a $\lambda_0/2$ transmission line, were measured. If the signals in the two paths have equal amplitude, linear phase characteristics and slight group-delay mismatching due to the $\lambda_0/2$ transmission line, then a perfect signal cancellation would be obtained around the center frequency. However, a signal at a ±100 MHz frequency offset would be partially cancelled due to its group-delay time mismatching. As a result, group-delay matching is shown to be important on broadband signal cancellation, in addition to the amplitude and phase matching.

Design of an Equal Group-delay Signal Canceller

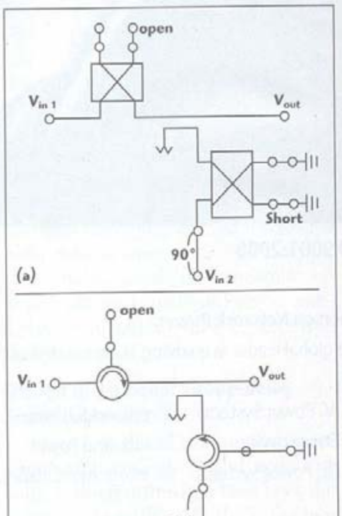
Figure 4 shows transmission lines terminated with short and open circuits. If the transmission lines have the same electrical length, the reflection signals are $-1e^{-j2\theta}$ and $1e^{-j2\theta}$, respectively. The reflection signals are out-of-phase, but their group-delay time is the same. Even though the input signal condition and the length of transmission line are changed, these properties are not. ***Figure 5*** shows the block diagrams of the proposed first loop signal cancellers of the feed-forward amplifier. The two input signals of the hybrid-based circuit are fed to a 3 dB hybrid for which the coupling and the through ports are terminated with open and short circuits, respectively. The two output signals of the 3 dB hybrids are out-of-phase and fed into an in-phase combiner. Since the two input signals in the final output port experience the same group-delay time and are out-of-phase, a perfect signal cancellation is obtained. The 3 dB hybrid is used to obtain a good reflection characteristic. The 3 dB hybrid could be replaced with a circulator. However, the frequency dependence of a circulator is more severe than for a 3 dB hybrid. So the use of hybrids is preferable in the first loop signal canceller. ***Figure 6*** shows the block diagrams of the second loop signal canceller of the feed-forward amplifier. The operating principle of the second loop canceller is almost the same except for the 90° phase compensation of the loose coupling hybrid.

MEASURED RESULTS

To show the validity of a feed-forward amplifier adopting the proposed signal cancellers, several circuits such as a main amplifier, an error amplifier, variable attenuators and variable phase shifters as well as the proposed first and second cancellers, using 3 dB hybrids, were fabricated. For comparison, a Wilkinson combiner and a 10 dB hybrid were also fabricated as conventional signal cancellers, where the operating frequency was 2.14 ±0.1 GHz. The feed-forward amplifiers used the same circuits except for the cancellers, because the cancellation results of the feed-forward amplifier depended on the electrical characteristics of the sub-circuits. The fabricated main and error amplifiers consisted of four transistor stages. The measured gain, maximum return loss and 1 dB compression point (P1dB) were 44.7 ±0.3 dB, –14 dB and 28.7 dBm, respectively. The variable attenuator and the variable phase shifter were of the reflection type for good reflection characteristics. The maximum attenuation and phase shifting range were 15 dB and 120°, respectively. ***Figure 7*** shows the first loop signal cancellation characteristics, using the conventional Wilkinson and the proposed signal cancellers. The input signal was cancelled more than 16.4 dB within 2.14 ±0.1 GHz with the conventional Wilkinson canceller. However, the proposed canceller can-



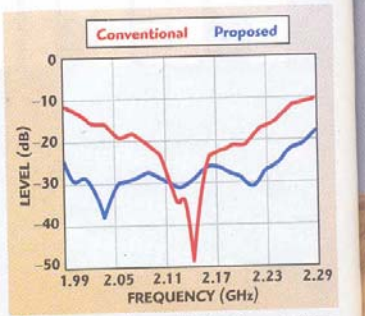
▲ *Fig. 5 Proposed first loop signal cancellers (a) using hybrid couplers and (b) using circulators.*



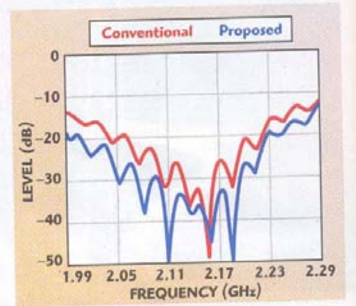
▲ *Fig. 6 Proposed second loop signal cancellers (a) using hybrid couplers and (b) using circulators.*

celled the signal more than 26.3 dB within the same frequency range. The frequency bandwidth where the signal was cancelled by more than 20 dB was broader than 300 MHz.

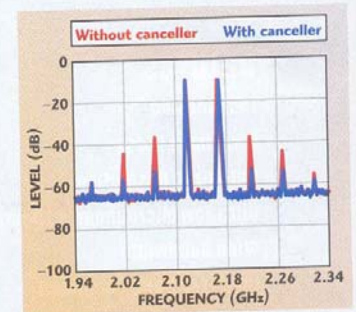
Figure 8 shows the second loop signal cancellation characteristic using the conventional canceller and the proposed canceller. The input signal was cancelled by more than 11.7 dB within 2.14 ±0.1 GHz with the conventional canceller. However, the proposed canceller cancelled by more than 15.2 dB within the same frequency range. The frequency bandwidth that the signal was cancelled more than 20 dB was improved from 94 to 173 MHz. With a two-tone signal amplification process, the improvements in the carrier-to-intermodulation (C/I) ratio were also measured, where the two-tone signals were 2115 and 2165 MHz, respectively. Before the error path of the second loop was connect-



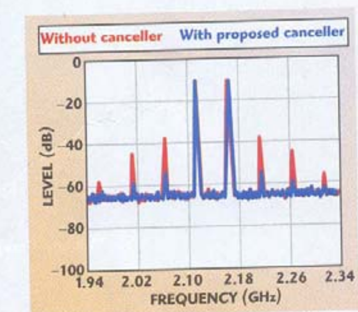
▲ *Fig. 7 Signal cancellation characteristics of the first loop using a conventional and the proposed cancellers.*



▲ *Fig. 8 Signal cancellation characteristics of the second loop using a conventional and the proposed cancellers.*



▲ *Fig. 9 Output characteristics of the feed-forward amplifier with and without conventional cancellers.*



▲ *Fig. 10 Output characteristics of the feed-forward amplifier with and without proposed cancellers.*

ed, the C/I ratio and the output power level at the feed-forward amplifier output port were just 26.84 dBc and 17.5 dBm/tone, respectively. When the amplifier was linearized with the conventional cancellers, the C/I ratio was improved to 42.63 dBc. ***Figure 9*** shows the output characteristics of the feed-forward amplifier with and without the conventional cancellers. The improvement of the fifth C/I was not good, whereas that of the third C/I was fairly good. That was due to the out-of-phase and group-delay mismatching of the cancellers in the feed-forward loop. When the amplifier was linearized with the proposed cancellers, the C/I ratio was improved to 48.03 dBc. ***Figure 10*** shows the output characteristics of the feed-forward amplifier with and without the proposed cancellers. The third C/I was improved as well as the fifth C/I. The comparison of the C/I measurements, between the conventional and the proposed feed-forward amplifier, shows that the proposed cancellers improve C/I over a broader band.

CONCLUSION

In this article, new signal cancellers are proposed that match simultaneously the phase and group-delay properties of the feed-forward loops. Conceptually, a feed-forward amplifier that adopts the proposed cancellers can cancel carrier signals in the first loop and IMD signals in the second loop perfectly over a broad band. IMT-2000, mobile Internet and wireless LAN using OFDM have a broader service frequency bandwidth than previous other communication services. A feed-forward amplifier, using conventional cancellers, is limited in linear frequency bandwidth, so that it cannot operate over the necessary frequency band. However, the proposed feed-forward amplifier can be linearized over the whole frequency band without a partition of the service band. The proposed feed-forward amplifier may be advantageous to communication service providers and amplifier manufacturers, because of better operating convenience and good manufacturing yield. ■

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