

# Useful Characteristics for Controlling the Cancellation Performance and Center Frequency of a Linearization Loop

Sanggee Kang and Sungyong Hong

*ABSTRACT*—The cancellation performance of a linearization loop is limited by the degree of an amplitude imbalance and a phase imbalance. A delay mismatch causes a phase variation as a function of frequency. Therefore, the cancellation performance and linearization bandwidth are limited by a delay mismatch. The expression for the effects of an amplitude imbalance, a phase imbalance, and a delay mismatch on the characteristics of a linearization loop is derived and analyzed. The simulation results are compared with the results obtained by means of using a commercial simulation tool and the exact agreement is reported. The derived equation could be used in designing a linearization loop and predicting the cancellation performance of the linearization loop usefully. Some useful characteristics, known from the simulation results obtained by using the derived equation, of a linearization loop for designing and implementing feedforward amplifiers are described in detail.

*Keywords*—Linearization, amplitude imbalance, phase imbalance, delay mismatch.

## I. Introduction

Feedforward has several advantages in linearization bandwidth, cancellation performance, and dynamic range over other linearization methods such as feedback, predistortion, and linear amplification with nonlinear components [1]. Therefore, feedforward amplifiers are widely used in mobile communication systems. The linearization characteristics of a linearization loop in a feedforward amplifier are determined by

how well the differences of gain, phase, and time delay between two paths composed of the linearization loop are minimized. The linearization principle of a linearization loop can be used not only for linearizing power amplifiers but also for measuring and reducing the phase noise of a voltage controlled oscillator (VCO).

The performance of a linearization loop limited by an amplitude imbalance, phase imbalance, and delay mismatch is described in [2], [3]. The effects of those parameters on the cancellation performance, and the linearization bandwidth of a linearization loop, are separately explained, that is, the effects of the amplitude and phase imbalance on the cancellation performance, and the effects of the delay mismatch on the linearization bandwidth and cancellation performance of the linearization loop. In this letter, we derive an equation representing the linearization characteristics of a linearization loop to take into account the above three parameters simultaneously. And the useful characteristics, known from the simulation results obtained by using the derived equation, of a linearization loop for designing and implementing feedforward amplifiers are described in detail.

## II. Analysis of a Linearization Loop

The linearization principle is a cancellation principle, that is, a signal can be cancelled out when two signals of equal amplitude with an anti-phase are added together. If two paths in a linearization loop have a different delay time, then we cannot maintain a phase difference of  $180^\circ$  between the two paths at all frequencies, only at one frequency. Therefore, a linearization loop must have no delay mismatch in order to have an infinite linearization bandwidth. However, if we want to get rid of a

Manuscript received Oct. 18, 2004; revised Feb. 17, 2006.

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carrier of a VCO for measuring the phase noise of the VCO, then a linearization loop must have a large delay mismatch to cancel out the carrier only, without interfering with the phase noise of the VCO.

A signal  $S_1$  appearing at the output port after passing through a path among two paths made up of a linearization loop can be written as

$$S_1 = V_{1m} \cos\{\omega(t - \tau) + \phi\}, \quad (1)$$

where  $V_{1m}$  is the amplitude,  $\omega$  is the angular frequency,  $\phi$  is the initial phase, and  $\tau$  is the delay time needed to pass through the path. A signal  $S_2$  appearing at the output port after passing through the other path in the linearization loop for cancelling out  $S_1$  can be expressed as

$$S_2 = (V_{1m} + V_{am}) \cos\{\omega[t - (\tau + d_m)] + \phi + 180^\circ + \theta_m\}, \quad (2)$$

where  $V_{am}$  and  $\theta_m$  represent the amplitude and phase mismatch between  $S_1$  and  $S_2$  due to the difference of gain and phase characteristic between the two paths, respectively, and  $d_m$  is the delay mismatch. Therefore, the phase difference between the two paths,  $\theta_d$ , is given by

$$\theta_d = 180^\circ + \theta_m - \omega d_m. \quad (3)$$

Equation (3) shows that a constant phase difference can be maintained at all frequencies when a linearization loop has no delay mismatch. If there is a delay mismatch, we can adjust the phase difference of  $180^\circ$  at one frequency only. And we denote the frequency as  $\omega_s$ , representing the center frequency of the linearization bandwidth. As the delay mismatch is increased, the amount of phase mismatch is also increased. Therefore, the amount of phase mismatch is increased as the frequency departs further from  $\omega_s$ .

Figure 1 explains the fact described above so far. Figure 1(a) shows a phase variation of two paths having a different time delay; and  $d_2 > d_1$  in this case. The procedure adjusting the phase difference between the two paths to  $180^\circ$  at  $\omega_s$  is shown in Fig. 1(b). In Fig. 1(b),  $d_m = d_2 - d_1$ ,  $d_2 > d_1$ , and the shadow region represents phase mismatches. Figure 1(c) shows the slope of the phase mismatch according to the sign of the delay mismatch. If  $d_m = 0$ , a phase difference of  $180^\circ$  can be kept at all frequencies, but if  $d_m \neq 0$ , a phase difference of  $180^\circ$  can only be kept at  $\omega_s$ , and the phase mismatch is increased as the offset frequency from  $\omega_s$  is increased.

If we can adjust the phase difference to  $180^\circ$  at  $\omega_s$  using a phase shifter, then the phase difference between two paths can be written as

$$\theta_d = 180^\circ + (\omega_s - \omega)d_m + \theta_m. \quad (4)$$

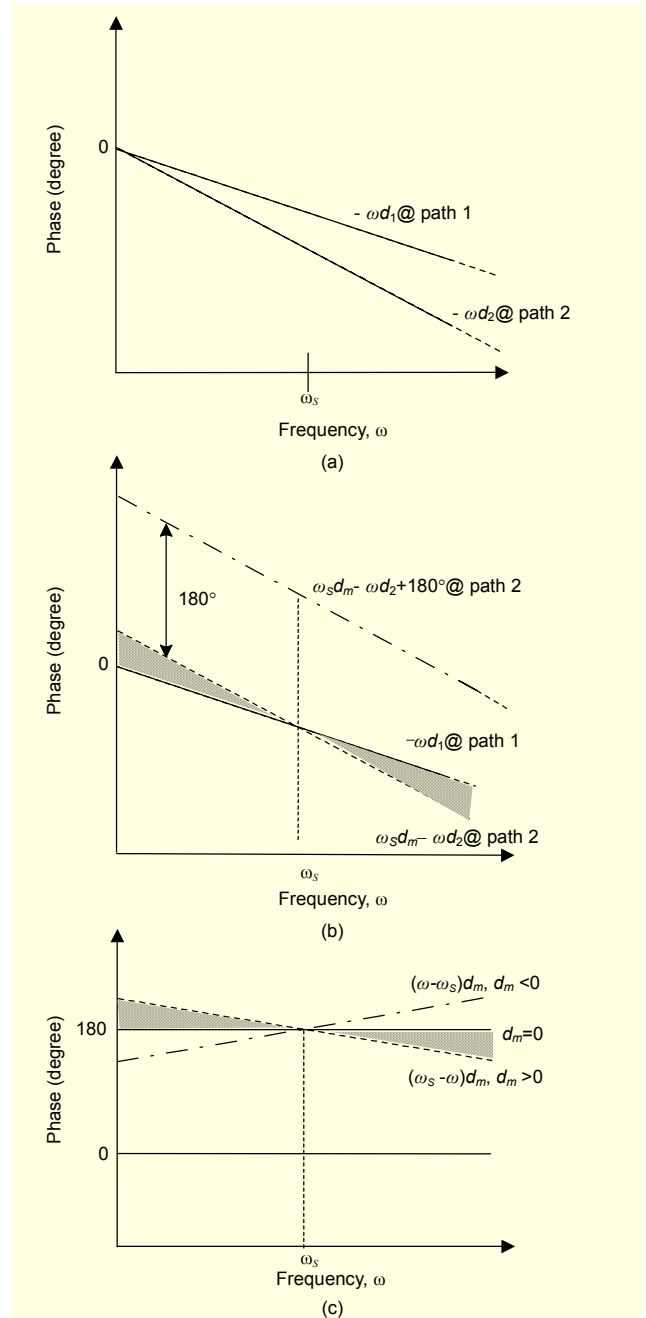


Fig. 1. Phase variation caused by a delay time: (a) phase variation of a path with a certain delay time ( $d_2 > d_1$ ), (b) phase variation when a phase difference is adjusted to  $180^\circ$  at  $\omega_s$ , and (c) the slope of a phase variation according to a delay mismatch.

Then, (2) can be rewritten as

$$S_2 = (V_{1m} + V_{am}) \cos\{\omega(t - \tau) + (\omega_s - \omega)d_m + \phi + 180^\circ + \theta_m\}. \quad (5)$$

The cancellation performance of a linearization loop is defined as the ratio of the output power of the linearization loop to the signal power to be cancelled out. Therefore, the cancellation

performance of linearization loop  $P_{cp}$  can be written as

$$P_{cp} = 1 + \alpha^2 - 2\alpha \cos\{(\omega - \omega_s)d_m - \theta_m\}$$

$$= 1 + \alpha^2 - 2\alpha \cos\left\{2\pi\left(\frac{\lambda_{err}}{\lambda_s}\right)\left(1 - \frac{f}{f_s}\right) + \theta_m\right\}, \quad (6)$$

where  $\alpha = (V_{1m} + V_{am})/V_{1m}$  and represents the amplitude imbalance between two signals, and  $d_m = \lambda_{err}/(\lambda_s f_s)$ , where  $\lambda_s$  is the wavelength at  $\omega_s$  and  $\lambda_{err}$  is the delay mismatch described as the difference of the electrical length.

Equation (6) shows the effect of amplitude, phase, and delay mismatch on the linearization characteristics. We can measure the delay mismatch of a linearization loop using a network analyzer. Equation (6), therefore, is usefully used for designing and implementing a linearization loop because a delay mismatch in time is used for describing the cancellation performance.

As a delay mismatch is increased, a phase difference between two paths is steeply varied in both frequency bands, the lower- and upper-side frequency bands from the center frequency  $\omega_s$ . Therefore, the larger delay mismatch causes the smaller linearization bandwidth. If we want to obtain a broad linearization bandwidth, the delay mismatch must be kept as small as possible. If there is no delay mismatch, the cancellation performance is limited by an amplitude and phase mismatch. In this case, however, the phase mismatch cannot be varied as the frequency is changed, and the linearization loop has a constant cancellation performance, which is independent on the frequency. If a linearization loop has a delay mismatch without an amplitude and phase mismatch, we can make the infinite cancellation performance at  $\omega_s$ . However, the cancellation performance at other frequencies except  $\omega_s$  is limited by a phase mismatch caused by a delay mismatch.

### III. Simulation Results

Figure 2 shows the cancellation performance of a linearization loop versus frequency when the linearization loop has a certain value of amplitude, phase, and delay mismatch. In order to demonstrate the validity of (6), we compare the simulation results from (6) with the results obtained by Libra series IV. Figure 2 shows that the simulation results obtained from (6) are exactly the same as the results obtained by using Libra. In Fig. 2, case 1 has a larger linearization bandwidth than case 2, because in case 2 the  $0.2\lambda_s$  increment of the delay mismatch gives rise to the steep slope of the phase variation versus frequency. In case 3, the linearization loop has a constant cancellation performance of -26.03 dB. And the cancellation performance is not changed by frequency because the delay time of the linearization loop is matched, that is, the two paths have the same delay time. The phase mismatch of  $2^\circ$  is maintained even though the operating frequency of the loop is changed in case 3. The cancellation

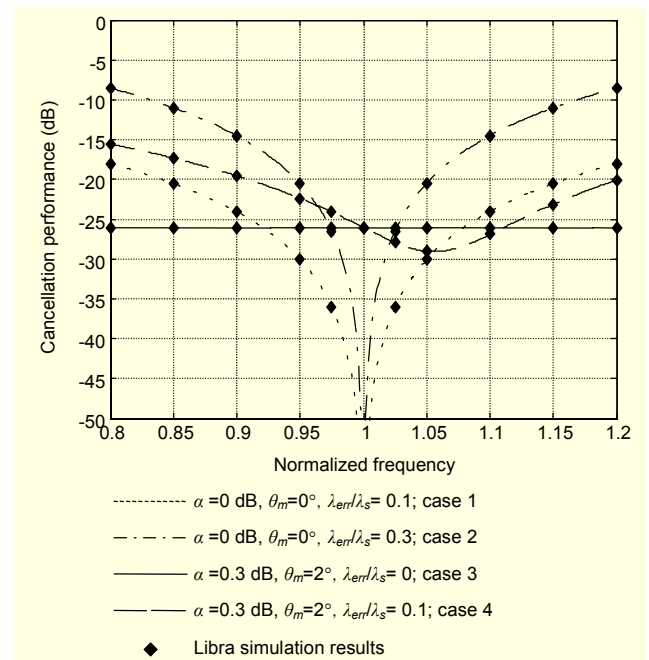


Fig. 2. The cancellation performance of a linearization caused by an amplitude imbalance, a phase imbalance, and a delay mismatch.

Table 1. Linearization bandwidth and cancellation performance of a linearization loop (the linearization loop has no phase mismatch at the center frequency,  $f_{scale} = (1\text{GHz}/f_c)$ ,  $f_c$  is the center frequency in GHz, CP\_dB is the cancellation performance in dB).

CP_dB	$d_m=0.1$ ns $\alpha=0.1$ dB	$d_m=0.3$ ns $\alpha=0.1$ dB	$d_m=0.5$ ns $\alpha=0.1$ dB	$d_m=0.3$ ns $\alpha=0.3$ dB	$d_m=0.5$ ns $\alpha=0.3$ dB
30 dB	$(9.2 \times f_{scale})\%$	$(3.0 \times f_{scale})\%$	$(1.88 \times f_{scale})\%$		
25 dB	$(17.4 \times f_{scale})\%$	$(5.8 \times f_{scale})\%$	$(3.48 \times f_{scale})\%$	$(4.56 \times f_{scale})\%$	$(2.76 \times f_{scale})\%$

performance of case 4 is better than case 3 over the normalized frequency band of 1 to 1.111. The delay mismatch of  $0.1\lambda_s$  makes a better phase balance than case 3 over the normalized frequency band of 1 to 1.111. However, the phase mismatch of case 4 is larger than the phase mismatch of case 3 at other frequencies. Therefore, the cancellation performance of case 4 is lower than case 3, except for the frequency band of 1 to 1.111.

In general, it is difficult to measure the delay mismatch in wavelength, but the delay mismatch can be easily measured in time. Therefore, (6) can be useful for calculating and predicting the cancellation performance of a linearization loop having a delay mismatch that can be measured in time. The delay mismatches of  $0.1\lambda_s$  and  $0.3\lambda_s$  at the frequency of 1GHz correspond to 0.1 ns and 0.3 ns, respectively. Some simulation results of the linearization bandwidth and cancellation performance are listed in

Table 1. A linearization loop has an amplitude imbalance of 0.1 dB, delay mismatch of 0.1 ns, and no phase mismatch. Then, the linearization loop has a 30 dB linearization bandwidth of 9.2%. The 30 dB linearization bandwidth of 9.2% equals 92 MHz at a center frequency of 1 GHz and 46 MHz at 2 GHz. If the amplitude imbalance is more than or equal to 0.3 dB, the linearization loop cannot obtain a cancellation performance of 30 dB. Table 1 shows the larger the delay mismatch is, the smaller the linearization bandwidth that is achieved.

Figure 3 shows that the center frequency of a linearization loop can be moved to the wanted frequency by controlling the amount of phase mismatch. If the phase mismatch is increased, the center frequency of the linearization loop is also increased without any degradation in the cancellation performance and linearization bandwidth with the assumption that there are no amplitude and phase variations generated by changing the phase mismatch. These results can be effectively used to change the operation frequency of a linearization loop without manual tuning. If we want to change the operating frequency band of a linearization loop, then we can change the operating frequency band by adjusting the amount of the phase mismatch of the linearization loop without a cancellation performance and linearization bandwidth degradation. These characteristics can be efficiently used in feedforward amplifiers for automatically changing the operating frequency band to other frequency bands.

of a linearization loop in terms of amplitude, phase, and delay mismatch. A phase mismatch can be adjusted by a phase shifter, but a delay mismatch cannot be adjusted. Therefore, a delay mismatch is kept as small as possible for the cancellation performance and linearization bandwidth that we want. However, a delay mismatch can be used for moving the center frequency of a linearization loop even if the cancellation performance and linearization bandwidth are limited by the delay mismatch.

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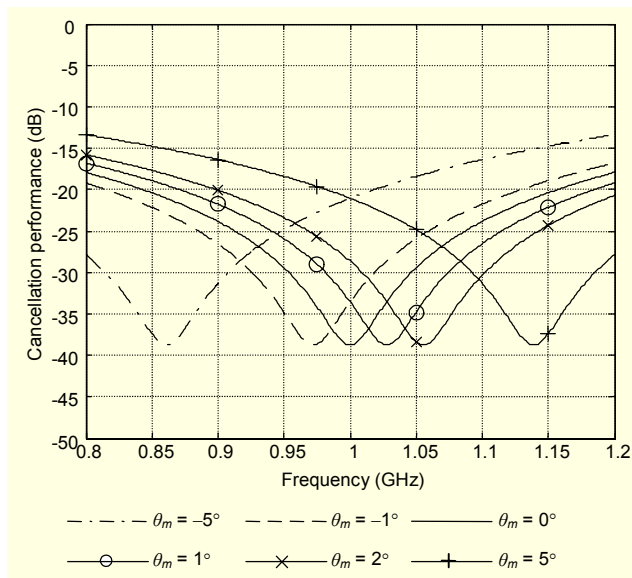


Fig. 3. The movement of the center frequency of a linearization loop by adjusting an amount of the phase mismatch ( $d_m=0.1$  ns,  $\alpha=0.1$  dB).

## IV. Conclusions

We have derived an equation for describing the performance