Digital Predistortion Linearization of Frequency Multipliers

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Abstract — **This paper presents a novel technique to linearize frequency multipliers for use with modulated signals. Using amplitude and phase mapping functions, a modulated signal may be translated to an integer multiple of the carrier frequency with minimal distortion. To validate this technique, a Schottky-diode frequency tripler was built to transmit digital signals at 2.46 GHz with an 820 MHz input carrier frequency. Measured results show that with an IS-95B input signal, the digital predistorter achieved 26 dB of improvement in the Adjacent Channel Power Ratio (ACPR) at 2.46 GHz. Its output Error Vector Magnitude (EVM) was 13% with predistortion, whereas it was near 100% without predistortion. Additionally, an adaptive digital predistorter was designed, and simulation showed a 40 dB improvement in IMD with 4-tone signal input.**

I. Introduction

Predistortion linearization is a well-known linearization technique used for reducing distortion in RF power amplifiers (PAs) [1], [2]. Additionally, recent work has also been done on predistortion linearization of mixers [3], [4]. The method involves modifying the device input signal to counteract the signal distortion that arises from gain compression (AM-AM distortion), and phase deviation (AM-PM distortion). This is often done by performing mathematical operations on the baseband signals using digital signal processing. The predistorted signals are then upconverted to the operating frequency and applied to the PA input. The RF PAs used in such systems are generally operated in class-AB as a means to trade off linearity for efficiency. Intermodulation distortion (IMD) product may be suppressed by 10-20 dB.

For many mobile-based communication applications, dual-band capability is necessary for compatibility and multi-functional system integration. In addition, most commercialized dual-band RF front-end systems accommodate two separate RF chains for different bands placing overhead on the material cost and physical size of the equipment. Therefore, it is desirable to use a frequency multiplier so as to avoid a separate upconverter and PA chain. For constant envelope modulations, frequency multiplication may be used to translate the signal frequency [5]. One could conceive of a dual-band transmitter that is a PA in one mode, and a frequency multiplier in another. The problem with frequency multipliers is that they severely distort AM modulation. Such distortion causes increased EVM and ACPR.

Generally, frequency multipliers are highly nonlinear devices, and are usually relegated to multiplying unmodulated local oscillator (LO) signals. However, if properly done, predistortion linearization may be performed to linearize such strong nonlinearities to achieve the equivalent of the frequency translation of a modulated carrier. This paper presents a simple theory of frequency multiplier linearization, and validates the concepts by applying them to a Schottky-diode frequency tripler. To the best of the authors' knowledge, this is the first report of predistortion being used in conjunction with RF frequency multipliers.

II. Bandpass Transfer Characteristics

When a bandpass waveform is fed into a memoryless nonlinear device, its output signal contains harmonics and intermodulated components of the input signal.

Consider a device whose output $y(t)$ is given by

$$y(t) = \sum_{n=0}^{\infty} a_n x^n(t) = \sum_{n=0}^{\infty} a_n \left\{ \mathrm{Re}\left[x_L(t) \cdot e^{j\omega_0 t} \right] \right\}^n , \quad (1)$$

where $x(t)$ is the bandpass input of the device, $x_L(t)$ is the lowpass complex envelope of $x(t)$, and ω_0 is the carrier frequency. In most cases, a nonlinear device is characterized by the input and output relationship at the same frequency (first zone transfer characteristic). In general, the n^{th} harmonic bandpass output $\tilde{y}_n(t)$ can be derived from (1) using the Chebyshev transform [6]:

$$\tilde{y}_n(t) = \sum_{m=0}^{\infty} \frac{a_{2m+1}}{2^{2m}} \binom{2m+1}{m+\frac{n+1}{2}} \left| x_L(t) \right|^{2m-n+1} \mathrm{Re}\left[x_L^n(t)\, e^{jn\omega_0 t} \right]. \quad (2)$$

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For example, a frequency tripler has its bandpass output at three times the input frequency, and has a third zone bandpass output of

$$\tilde{y}_3(t) = \sum_{m=1}^{\infty} \frac{a_{2m+1}}{2^{2m}} \binom{2m+1}{m+2} |x_L(t)|^{2m-2} \; \mathrm{Re}\left[x_L^3(t) e^{j3\omega_o t} \right]$$
$$= \sum_{m=1}^{\infty} \frac{a_{2m+1}}{2^{2m}} \binom{2m+1}{m+2} |x_L(t)|^{2m+1} \; \mathrm{Re}\left[e^{j3\angle x_L(t)} e^{j3\omega_o t} \right], \quad (3)$$

where $\angle x_L(t)$ is the phase angle of the complex envelope of the input signal. Most parts of Eq. (3) look very similar to the first zone case, except that its major coefficient is $a_3/4$, which means that $|x_L(t)|^3$ is dominant, resulting in the power transfer slope of 3:1. This indicates that the amplitude modulation that is present in the input signal will be highly distorted. However, it also implies that a predistortion operation using the cube-root function may act to correct the transfer characteristic to 1:1, if higher order coefficients are small enough to be neglected. Another point to be mentioned is that the frequency tripler multiplies original phase information by three. We refer to this as PM-PM distortion. Thus, the major phase distortion component can be compensated by dividing the input phase by three. Additionally, since Chebyshev transforms are not meant to be applied to phase, any AM-PM distortion present in the first zone transfer characteristic must also be divided by three to compensate for the phase multiplication. Thus, predistortion of frequency multipliers should compensate for the PM-PM distortion as well as the AM-AM and AM-PM distortion.

III. TEST CIRCUIT DESIGN AND CHARACTERIZATION

For the validation of our predistortion theory, a simple frequency tripler was design and constructed as shown in Fig.1.

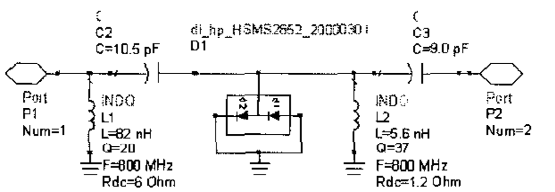


Fig. 1 Schematic of the Schottky-diode frequency multiplier.

The soft limiter characteristic exhibited by this Schottky-diode limiter turned out to be a good way to test the feasibility of this predistortion on a frequency multiplier since it has enough nonlinearity to create a significant third harmonic, while maintaining a 3:1 slope over a wide range of input power. Fig.2 shows the measured baseband transfer characteristic of the tripler.

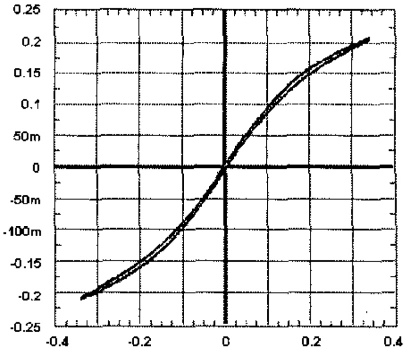


Fig. 2 Baseband transfer characteristic of the diode tripler.

Obviously, there is some compression at high input magnitudes that is inherent in the limiter design. The 1st and 3rd zone characteristics can be extracted from this graph by the Chebyshev transform, and they can be extracted experimentally by sweeping the input power and measuring the output powers at corresponding frequencies. A continuous wave input signal at 820 MHz was power swept, and the results are shown in Fig.3.

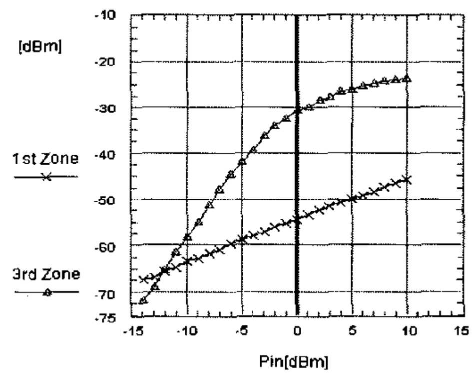


Fig. 3 First and third-zone transfer characteristics of the diode tripler.

The third zone curve shows a 3:1 slope over a range of almost 15 dB. The first zone is suppressed by the matching circuits, indicating good conversion efficiency into the harmonic bands. While the diode limiter serves as a useful circuit to validate the theory, the conversion loss is quite high (over 35 dB) in the range of dominant third order operation. A more practical approach would be to use active elements (BJTs or MESFETs) to achieve some conversion gain in the harmonic generation process.

IV. DIGITAL PREDISTORTION SYSTEM DESIGN

A non-adaptive baseband digital predistortion linearization algorithm was designed in Matlab. The predistorter has polynomial-based indirect architecture that is efficient since we need to calculate only the inverse model of the nonlinear device [7]. Its coefficients were extracted from the measurements shown in Fig.2, and Fig.3. Using the polynomial model, a predistorted signal file was generated and loaded into an Agilent E4432B arbitrary waveform signal generator. The upconverted RF sign was then applied to the circuit shown in Fig.1. The result of the predistortion system shown in Fig.1 is shown in Fig.4. The original input was an IS-95B signal at 820 MHz. The output signal was taken at 2.46 GHz. The peak-to-average ratio (PAPR) of the signal was 6.4 dB. Without the predistortion, the output signal was spread over 3 MHz, and its ACPR was almost 0 dBc. This was mainly due to the frequency and phase multiplication of the modulated signal through the tripler circuit. The digital predistortion improved the ACPR by 26 dB at 885 kHz offset from the center frequency. However, the ACPR deteriorated by 5 dB as the offset frequency increases. We suspect that this degradation resulted from higher order terms that were not treated in the truncated-polynomial predistorter. A more sophisticated algorithm could be employed to identify these coefficients and improve the response. The in-band EVM was reduced from nearly 100% before predistortion to around 13%. Fig.5 shows the constellation of the frequency tripler (a) without and (b) with predistortion. Note that the symbol detection was completely impossible without the predistortion.

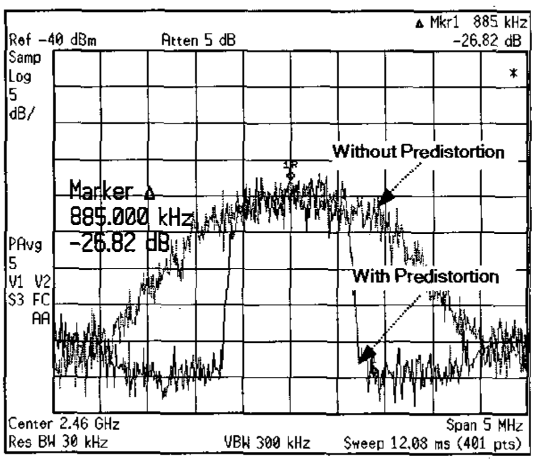
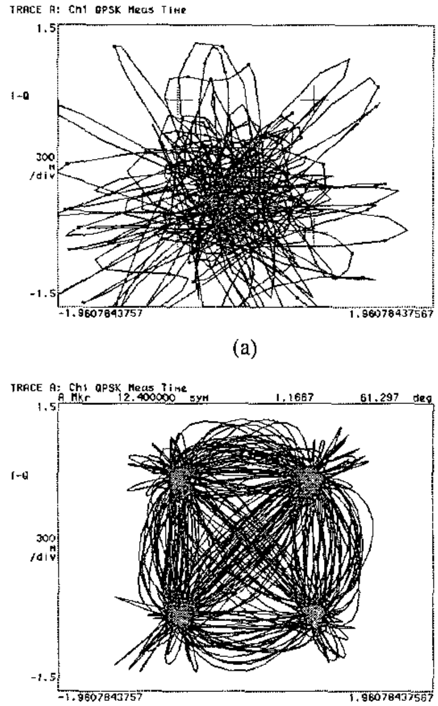


Fig. 4 Output spectrum of the presented diode tripler with and without predistortion measured using an Agilent E4404 spectrum analyzer.



(a)

(b)

Fig. 5 QPSK constellation of the diode tripler (a) without predistortion, and (b) with predistortion. These results were measured using an Agilent HP89410 vector signal analyzer.

V. LUT-BASED PREDISTORTION RESULTS (SIMULATION)

Although the analytic approach to predistort the diode tripler produced results sufficient to validate the theory, the nonlinearities that were higher than the order of the polynomial could not be fully compensated. In order to accomplish full compensation for the higher order terms, a an adaptive look-up table (LUT) implementation, rather than the fixed polynomial based method described in the last section, is more desirable, although somewhat more complex to implement. To show the possible improvements of such an adaptive system, the Schottky-diode frequency tripler was simulated with an adaptive LUT-based predistorter implemented in Agilent ADS. The model included separate LUTs for amplitude and phase corrections. However, the operation of the phase LUT is different from the conventional AM-PM LUT since the nonlinear device highly distorts the phase by the multiplicative operation (PM-PM), as well as by the usual AM-PM distortion. A four-tone test signal was used for the simulation. The tones were separated by 1.07 MHz on each side with the 2.14 MHz separation in the middle. The PAPR of the signal was 6.1 dB, about the same as the CDMA signal discussed in the last section. Fig.5 shows the results with and without the predistortion. As shown in this figure, the IMD without predistortion dramatically increased the bandwidth of the original input signal. After predistortion, the 3rd-order IMD was improved to be better than 40 dBc over three times in input signal bandwidth. Further improvement in IMD was limited by the dynamic range of the original signal.

Fig.6 shows the LUT entry after simulation, and this represents the gain versus input magnitude. The major predistortion gain should compensate for the 3rd-order distortion; therefore, the predistortion gain basically has to be of the form of $\sqrt[3]{(1/x^2)}$. This figure validates the idea by showing a nearly linear negative slope of 3:1 for the most regions as plotted on a logarithmic scale.

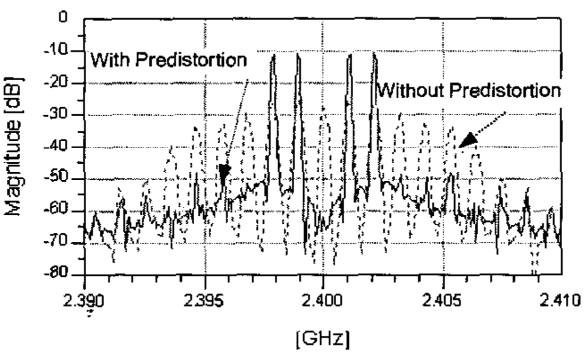


Fig. 6 Simulated output spectrum of LUT-based predistorter for the diode tripler with a 4-tone input.

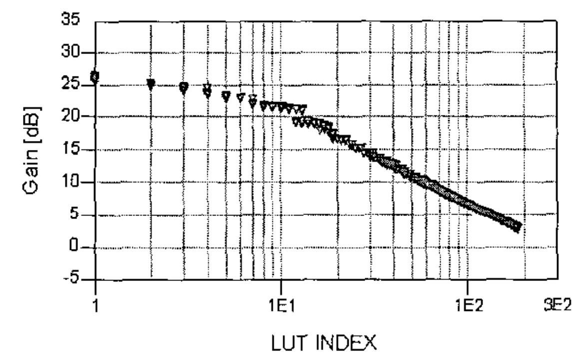


Fig. 7 Lookup-table results for the 4-tone input after adaptive predistortion of the diode limiter model.

VI. Conclusions

A predistorted frequency multiplier was suggested as a possible solution for a multi-band RF transmission system. A theory, based on baseband predistortion of the input envelope, was proposed to compensate for the highly nonlinear distortion of the frequency multiplier. To verify this theory, a Schottky-diode frequency tripler was built for the frequency multiplication of an IS-95B CDMA signal. A fixed predistortion algorithm was implemented to correct the AM-AM and PM-PM distortion for third order nonlinearities. The predistortion system, implemented on a testbed, achieved 26 dB improvement of the ACPR with an EVM of 13%. Without predistortion, those metrics were approximately 0 dB and 100%, respectively. A simulation model implemented on ADS showed that a more sophisticated LUT-based digital predistorter can adaptively correct for AM-AM, PM-PM, and AM-PM distortion to improve IMD to better than 40 dBc.

From the results of our research, we can conclude that it is feasible to use predistorted frequency multipliers to realize a multi-band, multifunctional transmitter by only changing the driving conditions of the transmitter rather than switching between entire RF upconverter chains. Such architectures may result in significant cost reductions in multi-band wireless terminals.

References

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