Injection schemes for TWT Linearization

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A. Introduction

Traveling Wave Tube (TWT) amplifiers, used in communication and ECM applications for their high power output, are nonlinear devices. This leads to harmonic and intermodulation distortion in the output spectrum which compromises the device performance. In communication systems, intermodulation products (IMPs) lead to adjacent channel interference while in ECM applications, harmonic generation adversely affects the efficiency at the fundamental.

In this paper we investigate various linearization schemes based on signal injection to condition the output spectra. We focus primarily on IM3 (third-order intermodulation) suppression for two-tone drive since the IM3s, being closest to the fundamentals, are the main concern in a communication system. Two primary techniques investigated are second harmonic injection ([1], [2], [3], [4]) and IM3 injection. These involve injecting amplitude and phase optimized harmonic and IM3 signal respectively, to suppress the inherently generated IM3 at the output of the TWT. We also propose a scheme based on simultaneous injection of both second harmonic and IM3 that offers the prospect of eliminating the need for precise phase control of the former two schemes.

B. The Physics of Injection Suppression

Based on approximate analytical solutions to the spectral TWT model S-MUSE [5], it can be shown that the net voltage at a particular frequency f_l can be represented as a sum of complex exponential modes:

$$V_l(z,t) = \left\{ A_l^{dr} e^{(\gamma_l^{dr} z)} + \sum_q A_l^{nl[q]} e^{(\gamma_l^{nl[q]} z)} \right\} e^{i f_l \omega_0 \left(\frac{z}{u_0} - t \right)} \qquad (1)$$

where the superscript "dr" refers to driven quantities and the superscript "nl" refers to quantities generated by nonlinear interactions. The idea of all of the injection schemes is to adjust the amplitudes and phases of the injected signal such that the bracketed term in Eq. (1) is minimized at z = L, the TWT output. Each of the driven and nonlinear modes has a different wavelength and growth-rate characterized by the complex propagation constants γ_l^{dr} and $\gamma_l^{nl[q]}$. This is illustrated in the following figure, which shows two different modes interfering destructively to achieve cancellation at the output.

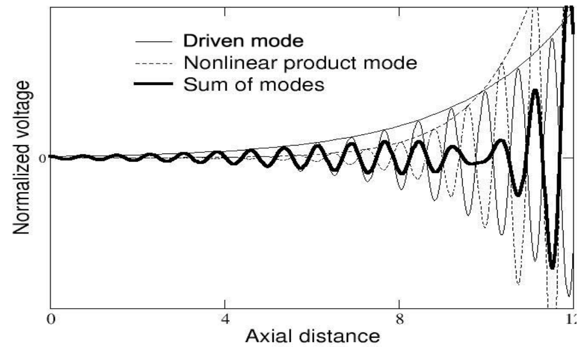

Fig. 1 Driven and nonlinear component modes sum up to give cancellation at output (z=L). (amplitudes and growth rates are scaled for best viewing)

Also it should be noted that contrary to earlier belief [6], suppression occurs only at the output and not throughout the tube. Experimental data shown in Fig. 2 for harmonic injection also confirms this fact. The tube used here is the XWING (eXperimental Wisconsin Nothrup-Grumman) TWT that has sensors along the helix.

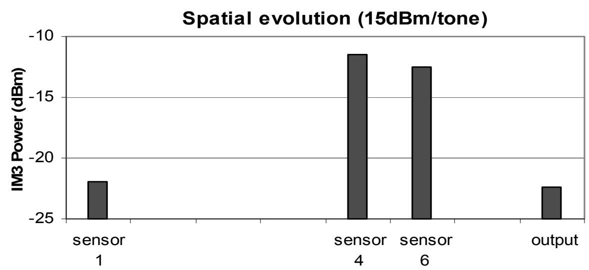

Fig. 2 Spatial evolution of IM3 along the axis of the tube while optimized for cancellation at the output.

C. Harmonic Injection forIM3 Suppression

By harmonic injection we refer to injecting $2f_b$ to cancel upper IM3 $2f_b - f_a$, where f_a and f_b are the fundamental drive frequencies with $f_a < f_b$. For such a situation, the solution given by Eq. (1) for $2f_b - f_a$ actually has no driven term. Instead there are two nonlinear terms in the sum – one formed by beating of the nonlinearly-generated harmonic $2f_b$ with f_a and the other by the beating of the injected harmonic $2f_b$ with f_a. The former term grows at a much faster rate (~ 3 times the fundamental growth rate) [7] than the latter (~ twice the growth rate of the fundamentals). Under optimal conditions, these two terms destructively interfere (are 180° out pf phase) at the output z = L. Fig. 3 shows the mode amplitudes and composite analytical solution for upper IM3 cancellation.

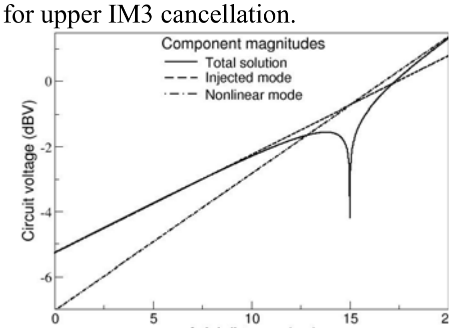

Fig. 3 Component modes in Harmonic injection scheme

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Experiments were carried out on the XWING tube with two drive frequencies of 1.90 and 1.95 GHz. Experimental results show significant suppression of 29.5 dB (56.7 dBc) for drive powers of 15dBm/tone and 32.4dB (55.2 dBc) for drive of 18dBm/tone.

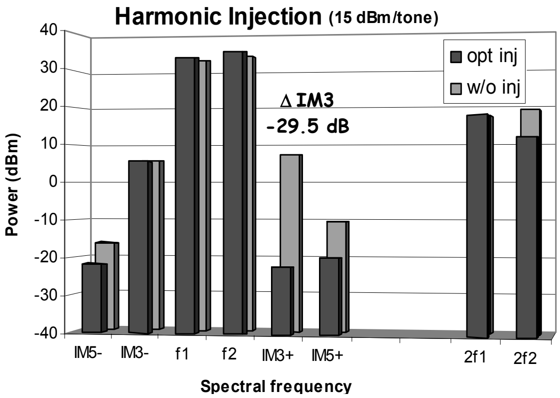

Fig. 4 Experiemtnal results for IM3 suppression by Harmonic injection

Similarly $2f_a$ can be injected to suppress the lower IM3, $2f_a - f_b$.

D. IM3 Injection for IM3 Suppression

For IM3 injection, there is one driven term at the frequency $2f_b - f_a$, in the solution of Eq. (1) and one nonlinear term produced by beating of the nonlinearly generated harmonic $2f_b$ with f_a. The driven mode causes the cancellation and again has a slower linear growth rate (~ same as fundamentals) than the nonlinearly generated term (~ 3 times the fundamental growth rate). Fig. 5 shows the mode amplitudes and composite solution for IM3 injection to cancel the upper IM3. The modes are 180° out of phase at the cancellation point z = L.

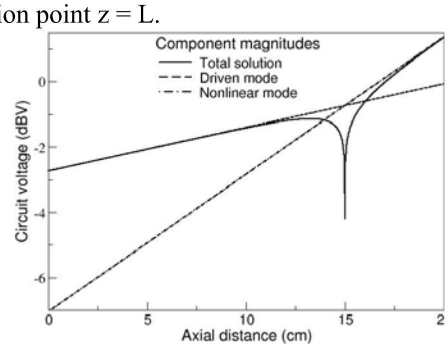

Fig. 5 Component modes in IM3 injection scheme

Experimental results show suppression of 26.6 dB (52.6 dBc) for drive powers of 15dBm/tone and 30.0 dB (51.7 dBc) for drive of 18dBm/tone. Similarly $2f_a - f_b$ can be injected to suppress the lower IM3.

Comparable suppression of ~30dB was obtained experimentally for both harmonic and IM3 injection schemes. Also it was found that for harmonic injection, both IM5s were also suppressed. However, for IM3 injection one of the IM5s was actually boosted. This aspect is currently being investigated and might provide hints regarding the preference of one scheme over the other.

E. Two frequency (Harmonic + IM3) Injection for IM3 Suppression

Sensitivity studies of the former two schemes show that the effectiveness of suppression is highly sensitive to both injected amplitude and phase. In practice, a high precision and stability of phase might be difficult to achieve, particularly at GHz frequencies. To avoid the need for precise phase control, we propose a scheme based on simultaneous injection of both second harmonic and IM3. For this injection scheme, there are three terms in (1) for the IM3 frequency. At the output these can be represented in a phasor diagram as seen in Fig. 6.

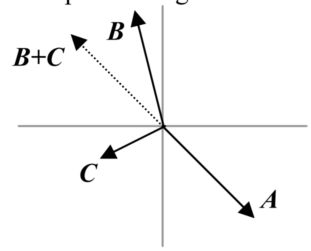

Fig. 6 Phasor diagram at TWT output for different modes in a two-frequency (harmonic+IM3) injection scheme.

Phasor ***A*** represents the nonlinear mode (due to inherently generated harmonic) that we wish to cancel. Phasors ***B***, ***C*** represent the driven term (due to injected IM3) and the nonlinear mode (due to injected harmonic). For cancellation, $|\boldsymbol{A}|=|\boldsymbol{B}+\boldsymbol{C}|$ and $\theta_{\boldsymbol{B}+\boldsymbol{C}} = \pi+\theta_{\boldsymbol{A}}$. For fixed fundamental input powers and fixed fundamental, injected harmonic and injected IM3 phases, if $\theta_{\boldsymbol{C}} - \theta_{\boldsymbol{B}} < \pi$ then the injected harmonic and IM3 powers can be adjusted to achieve IM3 cancellation.

While this technique was demonstrated analytically and by simulations, experimentally the lack of equipment to keep the phase constant as the power is varied presented a problem. However it was shown that suppression *is* possible with more than one signal injected. In the experiment, an injected IM3 was kept fixed in amplitude and phase and an injected harmonic signal was varied in both amplitude and phase. An upper IM3 suppression of 30.7 dB (58.0dBc) was observed.

These experiments have verified the conceptual feasibility of multi-tone injection for suppression of nonlinear distortion products and the mechanism represented by Fig. 6.

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