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 $f_i$ can be represented as a sum of complex exponential modes:

$$ V_i(z,t) = \left\{ \sum_{q} a^\text{dr}_l e^{i\gamma^\text{dr}_l z} \right\} + \left\{ \sum_{q} a^\text{nl}_l e^{i\gamma^\text{nl}_l z} \right\} e^{i (\omega_d t - \omega_0 t)} e^{i \phi_0} \left( \frac{z-L}{u_0} \right) $$

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 $\gamma^\text{dr}_l$ and $\gamma^\text{nl}_l$. This is illustrated in the following figure, which shows two different modes interfering destructively to achieve cancellation at the output.

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 Northrup-Grumman) TWT that has sensors along the helix.

C. Harmonic Injection for IM3 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 of phase) at the output $z = L$. Fig. 3 shows the mode amplitudes and composite analytical solution for upper IM3 cancellation.

* The authors were supported in part by AFOSR Grant 49620-00-1-0088 and by DUSD (S&T) under the Innovative Microwave Vacuum Electronics Multidisciplinary University Research Initiative (MURI) program, managed by the United States Air Force Office of Scientific Research under Grant F49620-99-1-0297.

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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.

Similarly 2\(f_h\) can be injected to suppress the lower IM3, 2\(f_h\) - \(f_a\).

D. IM3 Injection for IM3 Suppression

For IM3 injection, there is one driven term at the frequency 2\(f_h\) - \(f_a\), in the solution of Eq. (1) and one nonlinear term produced by beating of the nonlinearly generated harmonic 2\(f_h\) 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.

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.

Similarly, \(2f_h - f_a\) can be injected to suppress the lower IM3, 2\(f_h\) - \(f_a\).

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 2\(f_h\) - \(f_a\) 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.

REFERENCES