TABLE II
EXTRACTED SMALL-SIGNAL PARAMETERS OF THE TWO HBTs WITH $1 \times 20\ \mu m^2$ EMITTER AREA

	R_E (Ω)	R_B (Ω)	g_m (mS)	r_π (Ω)	C_π (pF)	C_{bci} (fF)	C_{bcx} (fF)
HBT-C	1.38	31.53	552	48.3	1.14	3.15	10.82
HBT-N	1.42	20.40	544	40.1	1.05	3.04	10.94

and HBT-N, respectively. This data clearly shows that the new process with SiN protection wall is working properly. Consequently, the base resistance, R_b, is reduced by 35% and maximum oscillation frequency, $f_{\max}$, is enhanced by 30% (from 162 GHz to 208 GHz). Since the base resistance does not affect the transit time, f_Ts of the two HBTs are quite similar, around 80 GHz.

IV. CONCLUSION

In order to reduce C_{bc} without increasing R_b, we have developed a new collector undercut process using a SiN protection sidewall. Since the base layer is intact during the collector undercut formation, it maintained a wide base contact region, while the region for conventional process is laterally etched. Due to the wide base contact region, the HBTs have a smaller current gain and smaller base resistance with similarly low C_{bc} compared to the HBTs with the conventional undercut process. We have demonstrated a 35% reduction of base resistance and a 30% increase of $f_{\max}$. $f_{\max}$ is enhanced from 162 GHz to 208 GHz for $1 \times 20\ \mu m^2$ emitter HBTs.

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Third-Order Intermodulation Reduction by Harmonic Injection in a TWT Amplifier

Michael Wirth, Aarti Singh, John Scharer, and John Booske

***Abstract*—A method for reducing the two-tone third-order intermodulation products arising from two carrier frequencies at 1.95 and 2.00 GHz is demonstrated in a traveling wave tube-distributed amplifier. The optimum amplitude and phase of an injected second harmonic and the resulting intermodulation suppression of up to 24.2 dB are examined for fundamental drive levels approaching saturation.**

***Index Terms*—Harmonic injection, IM3, nonlinear distortion, traveling wave tube.**

I. INTRODUCTION

When multiple carrier frequencies are amplified in a traveling wave tube (TWT) or other nonlinear amplifier, various order intermodulation products (IMPs) arise from the sum and difference of these frequencies. Certain IMPs are of concern since they lie close to the fundamental tones being amplified, thereby limiting the useful bandwidth of the amplifier. For example, in a simple excitation of f_1 and f_2, the two-tone third-order intermodulation products (IM3s) arise from $2f_1 - f_2$ and $2f_2 - f_1$, whereas fifth-order intermodulation products (IM5s) with nearby frequencies arise from $3f_1 - 2f_2$ and $3f_2 - 2f_1$. The work described here injects an additional signal into a TWT at the frequency of the second harmonic of the upper fundamental drive tone (f_2). When this injected signal at $2f_2$ is of the proper phase and amplitude, a significant reduction in the upper IM3 $(2f_2 - f_1)$ is observed.

This paper presents a detailed experimental examination of IM3 reduction using the harmonic injection technique in a TWT distributed amplifier. A recent study by Aitchison *et al.* [1] has demonstrated the effectiveness of this technique in narrowband, solid-state amplifiers at 835 and 880 MHz. They obtain substantial reduction in IM3 levels by both second harmonic and difference-frequency injection techniques. Work by Datta *et al.* [2] and Wöhlbier *et al.* [3] describe theoretical

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The authors are with the Department of Electrical and Computer Engineering, University of Wisconsin, Madison, WI 53706 USA (e-mail: scharer@cptc.wisc.edu).

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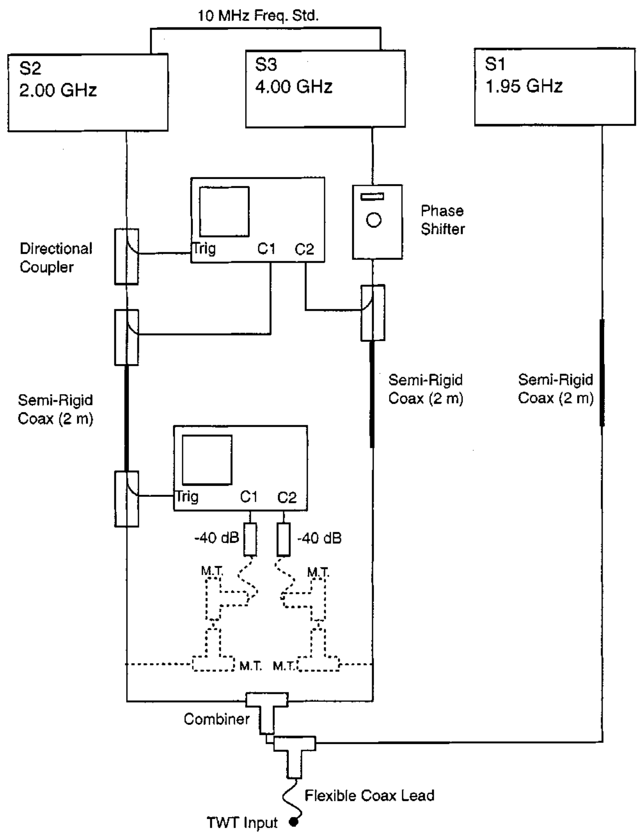
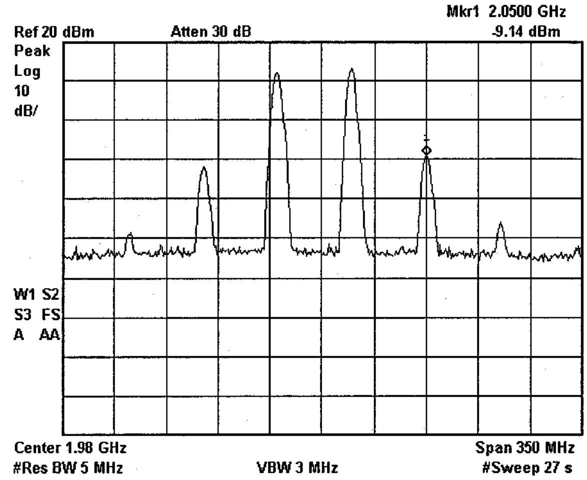
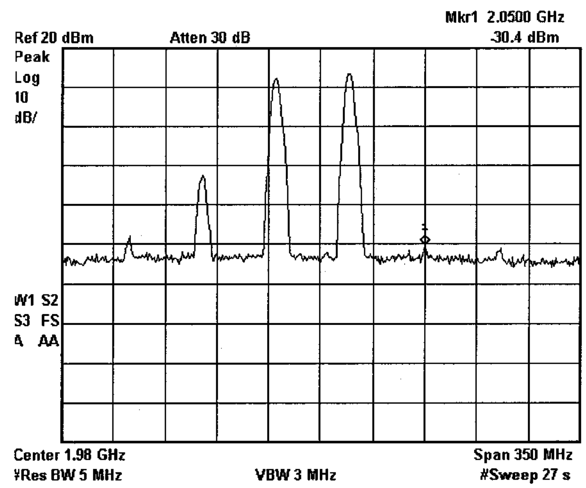


Fig. 1. Block diagram of single-harmonic injection experimental setup. Dashed lines show connections that were made with the TWT deactivated. Matched terminations (M.T.) were placed on open combiner ports.



(a)



(b)

Fig. 2. TWT output spectrum for two-tone, 15 dBm/tone input: (a) without and (b) with harmonic injection technique, showing 21.3 dB reduction in upper IM3 level.

models that predict similar behavior in TWTs. Other investigators [4], [5] have previously observed harmonic injection behavior in multitone driven TWTs, however, the injected signal amplitude and phase sensitivities were not experimentally studied in detail. Furthermore, Sauseng *et al.* [5] reported an IM3 suppression of ~7 dB, while we have found it possible to realize ~24 dB of suppression, with the TWT operating near saturation.

II. Experimental Device and Setup

A. Description of XWING TWT

The TWT used in this investigation, termed the Experimental Wisconsin Northrop Grumman TWT (XWING TWT), is a research version of a product manufactured by Northrop Grumman. This two-stage, helical TWT provides a moderate gain of 20–30 dB over a frequency range of 2–6 GHz, with saturation emerging above 21 dBm drive levels. In the following experiments, fundamental tone output levels are in the range of 33–37 dBm.

B. Experimental Setup

To maintain precise frequency and phase relationships, three frequency synthesizers were used to supply the two fundamental tones and the harmonic. Since the phase of the injected harmonic must be referenced with respect to the higher frequency fundamental, two Agilent 83 623B synthesizers were configured to share a common 10 MHz phase reference signal.

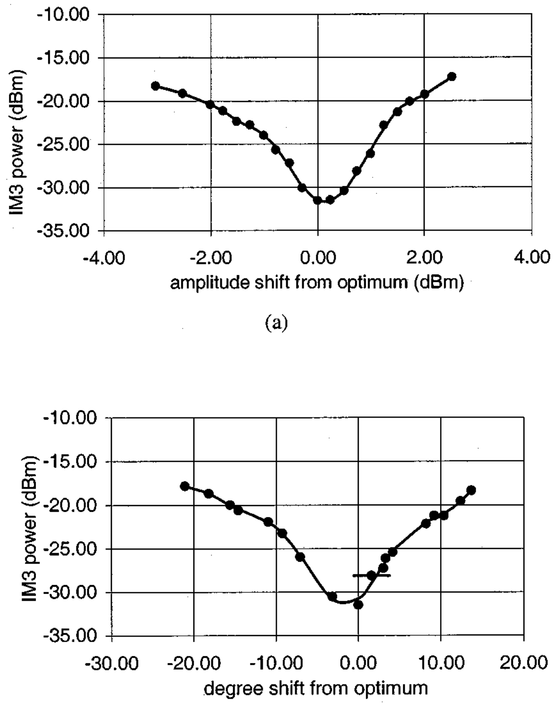
The upper fundamental and harmonic frequencies were set to 2.00 and 4.00 GHz, respectively. The 4.00 GHz signal was sent through a Narda 3752 phase shifter, allowing the fundamental-to-second harmonic phase relationship to be adjusted in real-time. The lower fundamental frequency of 1.95 GHz was supplied by a Wavetek 3520 synthesizer, providing a 50 MHz spacing between the two drive tones. The phase of this fundamental was not referenced to any other signal.

The phase relationship between the upper fundamental and the injected harmonic was monitored on two Agilent 86 100A wide-bandwidth oscilloscopes. A schematic of the TWT input network is shown in Fig. 1.

III. Experimental Procedures and Results

A. 15 dBm/Tone Fundamental Drive Levels

First, the 1.95 and 2.00 GHz fundamental drive tones were independently set to 15 dBm/tone at the TWT input tap, and the output spectrum was captured on an Agilent E4407B digital spectrum analyzer. This TWT output spectrum is shown in Fig. 2(a). Next, the 4.00 GHz second harmonic tone was injected at the TWT input and the phase was varied with respect to the 2.00 GHz fundamental to achieve the lowest IM3 level. The injected harmonic amplitude was then varied until further suppression in the upper IM3 level was observed. These phase/amplitude adjustments were iterated to ensure an optimum IM3 suppres-



(a)

(b)

Fig. 3. Sensitivity of 15 dBm/tone IM3 suppression to: (a) variation in injected harmonic amplitude and (b) variation in injected harmonic phase with respect to 2 GHz fundamental.

sion was achieved. This occurred with an injected harmonic amplitude of -2.1 dBm, or 17.1 dB below f_2.

The optimized TWT output spectrum is shown in Fig. 2(b). Notice that the upper IM3 is reduced by 21.3 dB, yielding an upper carrier to IM3 power ratio of 43.9 dB. The sensitivity of the IM3 level to variations in the injected harmonic amplitude and phase is shown in Fig. 3. In all cases, the IM3 power was measured to an accuracy of 0.2 dBm.

B. 18 dBm/Tone Fundamental Drive Levels

The experiment was repeated at higher input drive levels of 18 dBm/tone. The upper and lower fundamental tones were amplified by separate solid-state amplifiers (DBS DB94-0373 and Mini-Circuits ZHL-42W). Preamplifier harmonic content was verified at 30 dB below the carrier. Similar procedures were followed to determine the optimum phase and amplitude for the injected harmonic. For the optimum case, an IM3 reduction of 24.2 dB was observed, corresponding to an injected harmonic drive level of 0.9 dBm, or 17.1 dB below f_2. The IM3 suppression is greater than in the previous case, since the TWT is operating closer to saturation and nonlinear distortions are more pronounced. Consistent with the previous case, the improved upper carrier to IM3 power ratio is 43.6 dB. The optimum phase relationship between the injected harmonic and upper fundamental was measured at the TWT input tap. The 4 GHz injected harmonic was found to lead the 2 GHz fundamental by 47.5° with respect to the 2-GHz fundamental period.

IV. CONCLUSIONS

For two-tone excitation of a distributed TWT amplifier operating near 2 GHz with a 50-MHz separation, a significant reduction in the amplitude of the third-order intermodulation product was achieved by injecting a signal at the second harmonic of one of the drive tones with an optimum amplitude and phase. Reductions of third-order intermodulation products of 21.3 and 24.2 dB were observed for two-tone fundamental drive levels of 15 and 18 dBm/tone, respectively. While this experiment focused on the reduction of the upper third-order intermodulation product, it is expected that both may be reduced by adding another tone with the appropriate amplitude and phase at twice the lower fundamental frequency.

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A Novel Geometry for Circular Series Connected Multilevel Inductors for CMOS RF Integrated Circuits

Jaime Aguilera, Juan Meléndez, Roc Berenguer, José Ramón Sendra, Antonio Hernández, and Javier del Pino

***Abstract*—The scope of this brief is to introduce a novel geometry for circular series connected multilevel inductors. The idea is to improve the overlapping of the different metal layers that form the integrated inductor to maximize the magnetic flux shared by them and so the inductance. The performance of this new geometry has been compared with the conventional one, using Agilent HFSS field solver. After that, two multilevel inductors using this new geometry have been fabricated in a standard 0.6 μm three-metal CMOS process and measured.**

***Index Terms*—Electromagnetic simulations, multilevel integrated inductors, standard CMOS technologies.**

I. INTRODUCTION

GaAs-BASED technologies have dominated the fast growing communication market. But now, the miniaturization accomplished in standard Si technologies offers active devices with good characteristics in the low GHz frequency range, even in CMOS technologies. Nevertheless, there are several limitations for CMOS ICs. One of them is the inductor fabrication. CMOS processes use very low resistivity substrates. Therefore, the associated losses are large and high quality factor integrated inductors can not easily be achieved.

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J. Aguilera is with Escuela Superior de Ingenieros (TECNUN), 20018 San Sebastián, Spain (e-mail: jaguilera@ceit.es).

J. Meléndez and R. Berenguer are with Centro de Investigaciones Tecnicas de Gipuzkoa (CEIT), San Sebastián, Spain.

J. R. Sendra, A. Hernández, and J. del Pino are with the Instituto Universitario de Microelectronica Aplicada (IUMA), Las Palmas de Gran Canaria, Spain.

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