Combless Generator Tests Radar Warning Receivers

By H. Paul Shuch
Pennsylvania College of Technology

The conventional method for testing wideband or multiband microwave receivers is to utilize a combination of stable VHF or UHF signal source and a frequency multiplier or "comb generator" to produce harmonics in the bands of interest. The technique presented here eliminates costly harmonic multiplier components, employing nonlinearities in the receiver under test itself to generate the required test frequencies. Here is the author's account of this technique's development.

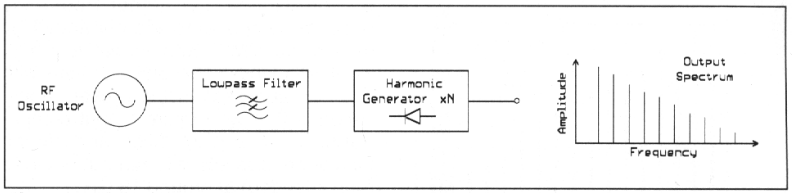


Figure 1. Basic comb generator block diagram.

As a consulting engineer, I am frequently employed by clients who have a clear idea of how they want to implement a given RF or microwave function, but require outside circuit design expertise. Generally, I try to give my clients exactly what they pay for. Every now and then, however, an unconventional solution presents itself which is so exciting that an enlightened client will dispense with his or her preconceived notions and try something new.

My client [1] had already secured a patent on RadaRanger™, a product for testing multiband police radar detectors. I was retained to finalize, perfect and package the required microwave circuitry. Three months into the project I had one of those "Aha!" insights for which all engineers pray: that the job can be done better, cheaper and more elegantly in the RF spectrum. My client was progressive enough to embrace the breakthrough. The results have been a new patent application, a new product line, and a new approach which other RF designers may find appealing.

Prior Art

There's nothing new about testing microwave receivers with lower-frequency oscillators and harmonic generators; I remember first seeing the technique in the MIT RadLab Series, circa 1945. All that's needed is a stable RF source and a non-linear circuit to generate harmonics, as depicted in Figure 1. If multiple microwave output frequencies are required, then an unfiltered comb of frequencies may be employed. The only constraint is that all the bands tested must share a common integer subharmonic.

Radio amateurs, whose original bands were all harmonically related, once used a 3.5 MHz crystal oscillator along with a diode comb generator to produce test signals in the 3.5, 7, 14, 21, 28, 56 and 112 MHz bands [2]. More recently, microwave hams have found that one "magic" frequency, 1152 MHz, is a subharmonic of calling frequencies at 2304, 3456, 5760, 10368 and 24192 MHz. An oscillator at 1152 MHz, followed by a broadband comb generator is often used as a "weak signal source" for testing microwave receivers in all five bands.

Now, how to generate the required harmonics? Step recovery diodes have been the traditional favorite [3,4], but at a recent Microwave Update conference two papers were presented which utilized the nonlinearities on MMICs [7,8]. Ward [7] started with a 96 MHz crystal controlled oscillator, then employed a rather expensive silicon bipolar MMIC to generate useful harmonics past 10 GHz. Wade [8] instead started with an 80 MHz TTL oscillator. Its harmonic-rich square wave output drives a much less costly MMIC to useful output in the 5 GHz region.

The original RadaRanger circuit, as envisioned by designers Robert Brocia and Marie Dagata, started with a sinusoidal oscillator at 1507 MHz, driving a similar MMIC comb generator circuit. The idea was for the oscillator's seventh, sixteenth and twenty-third harmonics to fall nicely within the X, K and wideband Ka-band police radar frequency allocations. The numbers all worked out fine. But, there were problems in generating adequate signal power at such high integer multiples, which is where I was called into the project.

A Conventional Solution

Bipolar MMICs are linear circuits, designed to produce sinusoidal, undistorted outputs in normal use. What is required for harmonic generation, however is a high degree of non-linearity. Fortunately, an overdriven bipolar junction transistor can be readily forced into saturation and cutoff, producing a first order approximation of a square wave whose Fourier series is rich in odd harmonics. This requires an input signal power on par with the amplifier's saturated output power. The output amplitude at a given odd harmonic is approximated by:

$$P_n \approx P_{sat} \div n \qquad (1)$$

provided the desired frequency component is an odd harmonic of the input frequency, and is at or below the transistor's transition frequency, that is:

$$f_n \leq f_T$$

But what if, as is the case in the present application, even harmonics are required as well as odd? Since MMICs are typically biased for midpoint conduction, they tend to be driven symmetrically into saturation and cutoff on alternate half-cycles. Such symmetrical clipping produces a square wave, rich only in odd harmonics. The key to even harmonic generation is to clip the sinusoidal waveform asymmetrically. This is

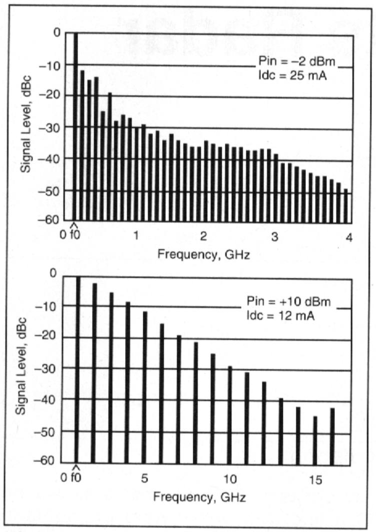


Figure 2. Harmonic generation vs. frequency for the Avantek INA-03170: (a) f_0 = 100 MHz. (b) f_0 = 1 GHz.

accomplished by moving the quiescent DC bias point away from the middle of the load line. To maximize comb generation while enhancing efficiency, simply drop the quiescent collector current of a single-stage bipolar MMIC in half, by increasing the external collector resistor value.

Figure 2, taken from [5], depicts the output spectrum of a three-stage silicon bipolar MMIC biased for harmonic generation. Notice that higher frequency spectral components are enhanced by driving the MMIC with a relatively high input frequency. The only problem with such an approach in the present application is that we require output components at 24 and 34 GHz, and silicon bipolar devices seem to run out of GaAs (pun intended) at around 18 GHz.

To produce comb elements in K and Ka bands, I suppose we're going to have to utilize GaAs FET technology. Figure 3, from [6], depicts the disappointing result. While a bipolar device brought us out to the eleventh harmonic before output amplitude dropped to –30 dBc, the GaAs MMIC shows a –30 dBc level at only the sixth harmonic. GaAs FETs are by nature highly linear devices. Although their operating frequency exceeds that of their bipolar counterparts, the linearity "advantage" makes it more difficult for them to generate substantial amounts of power at the higher harmonics. Back to the drawing board!

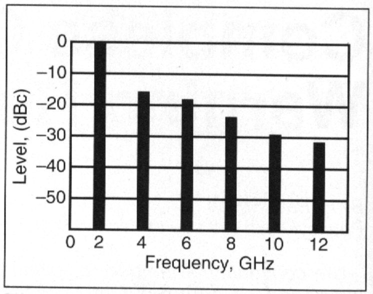


Figure 3. Typical GaAs MMIC comb generator output spectrum (Avantek MGA64135, f_0 = 2 GHz).

Step recovery diodes have long been utilized to produce harmonic-rich out-

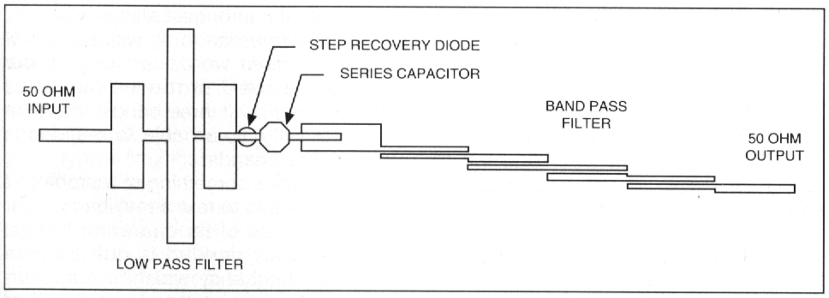


Figure 4. Typical SRD frequency multiplier.

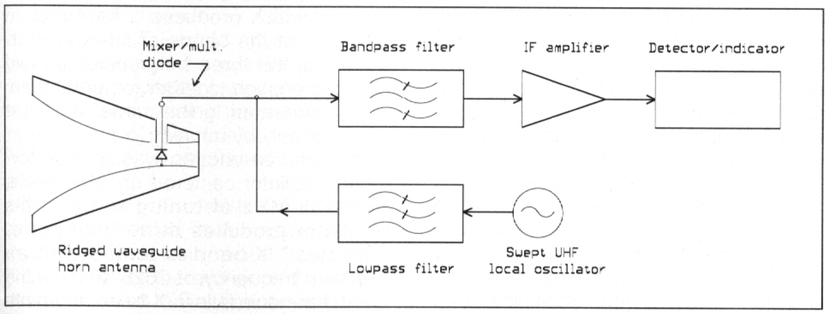


Figure 5. Typical multiband police doppler radar detector.

puts well into the microwave spectrum, their only drawback (relative to MMICs) being their lack of gain. However, they seemed a good compromise, in view of the frequency limitations of bipolar devices and the excessive linearity of GaAs FETs. A rule of thumb often cited for the harmonic output power of SRD comb generators is:

$$P_n = P_{in}(1/n) \tag{2}$$

Equation 2 seems to hold relatively well for tuned harmonic generators, such as that depicted in Figure 4 (from [4]). The output bandpass filter enhances specific spectral component, and 1/n power performance is readily achieved. However, it doesn't take long to see in the laboratory that an untuned output comb generator doesn't even come close to satisfying Equation 2. If we derive an equation for the output spectrum of a 1/n comb generator, the reason becomes painfully apparent:

$$\sum_{n=1}^{N}(P_n) = f_2 @ (P_{in} \div 2) + f_3 @ (P_{in} \div 3) + f_4 @ (P_{in} \div 4) + \cdots + f_N @ (P_{in} \div N) \tag{3}$$

If Equation 3 were true, then a SRD comb generator producing the second through fourth harmonics of its input signal would have a total output power of (1/2)+(1/3)+(1/4) = 1.08 times P_{in}, obviously a violation of the principle of conservation of energy!

A more realistic estimate of output power from an untuned SRD multiplier might be:

$$P_n = P_{in}(1/n^2) \tag{4}$$

which gives us a total power relationship of:

$$P_t = \sum_{n=2,3,4...}(P_{in} \div n^2) \tag{5}$$

which asymptotically approaches unity. But note that the higher order harmonics drop off quite rapidly in amplitude. Thus, for example, in order to utilize the SRD combline generator's 23rd harmonic for testing Ka band radar detectors we need to drive it at an amplitude of (23^2) = 529 times the required output amplitude. Conversely, if we have a given input power available to the SRD, its 23rd harmonic will be, at best, 529 times weaker. For the present project, we anticipated driving the SRD multiplier at about 1 mW input. Thus, its anticipated Ka band output power was on the order of 2 uW, just barely within the sensitivity specs of the receivers being tested.

But another problem arose — an attempt to breadboard a comb generator with a surface-mount packaged SRD was a dismal failure. Output was ample at X band, sub-marginal at Ka band and

Radar Band	X	K	Ka
Allocation (GHz)	10.475-10.575	24.05-24.25	34.2-34.4
n (harmonic)	x4	x9	x13
Oscillator Freq.			
2625 MHz	10.5 [in]	23.625 [low]	34.125 [low]
2645 MHz	10.58 [high]	23.805 [low]	34.385 [in]
2675 MHz	10.7 [high]	24.075 [in]	34.775 [high]

Table 1. RadaRanger™ frequency scheme.

nonexistent at Ka band! It turns out that the package transconductance of the SOT device is on the order of 2 uH [9], making this package entirely unmatchable at the higher microwave frequencies. The recommended solution: a bare chip SRD, thin-film fabrication, and attendant prohibitive fabrication costs, which nearly scuttled the RadaRanger project.

The Breakthrough

And then (just as depicted in the famous Sidney Harris cartoon of mathematicians at work), a miracle occurs. While playing around with the oscillator portion of the RadaRanger breadboard (comb generator now sadly abandoned), an X band radar detector which just happened to be turned on, and just happened to be on the bench, beckoned loudly. Curious, thought I, are there police cruising the neighborhood? Are they hot on the trail of some industrial spy, out to steal all my secret circuits? As I turned off the oscillator, the detector silenced. A few flicks of the power supply switch convinced me that the radar detector was somehow responding to my RF oscillator. Was its output frequency coincidentally on the superhetrodyne receiver's intermediate frequency? The spec sheet said it wasn't. Was my oscillator somehow rich in harmonic content? A quick check with the spectrum analyzer dispelled that possibility. What in the blazes was going on?

It hit me like the proverbial ton of bricks. The input circuit of this, and most other, radar detectors consists of a broadband, ridged waveguide horn antenna, with an SRD harmonic mixer diode mounted at its apex (Figure 5). An RF local oscillator signal is generated within the receiver; the mixer is supposed to generate harmonics of the LO, one of which will mix with the incoming X, K or Ka band radar signal to produce an IF output. But if the harmonic mixer can produce multiples of the LO signal, why can't it also product multiples of an incoming 1.5 GHz test signal? It can, and it did. Here was the serendipitous solution to our design dilemma.

The Next Step

If a 1.5 GHz oscillator can generate harmonics in the input diode of a police radar detector, and if one of those harmonics can trigger the X-band input of a multiband radar detector, can higher harmonics trigger the same detector's K and Ka band modes? Theory said yes, but practice indicated otherwise. When simultaneously excited at multiple bands, most radar detectors either default to indicating a single band threat (typically X band), or respond to the band with the strongest stimulus (which, since P_n varies as $1/n^2$, will also be X band). In other words, as long as our "magic number" produces harmonic components in all three bands, the radar detector will only be able to respond in one of those bands.

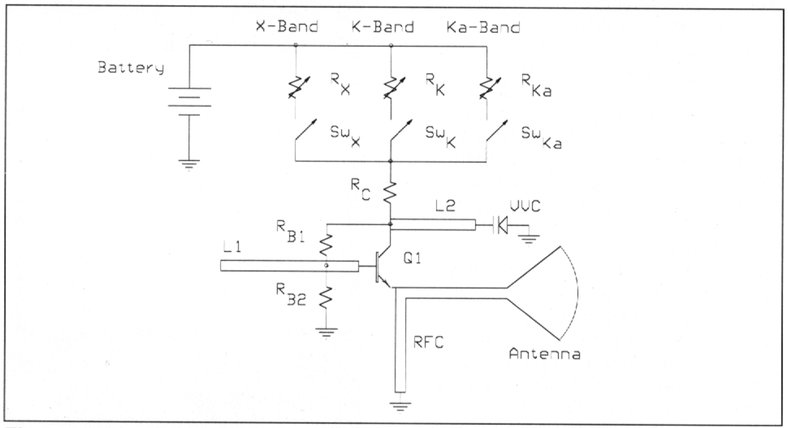


Figure 6. The RadaRanger™ multiband radar detector tester.

Which poses something of a problem if our objective is to test a multiband radar detector in all of its operating bands. What's really needed is not a single oscillator frequency which is a subharmonic of all three bands, but rather three separate oscillator frequencies, each of which produces a harmonic in only one of the bands of interest. Furthermore, the three frequencies should be close enough together to permit them to be generated in the same oscillator circuit, simply by retuning.

The solution chosen was a varactor-tuned oscillator centered on 2650 MHz, with ±25 MHz of tuning range. This oscillator produces three "magic frequencies." X-band is tested with an oscillator frequency of 2625 MHz — the fourth harmonic falls in X-band, the ninth harmonic falls just below the K band allocation, and the thirteenth harmonic is just below the Ka band allocation. K-band is tested by tuning the oscillator to 2675 MHz — the fourth harmonic is now too high for X band, the ninth harmonic falls within the K band allocation, and the thirteenth harmonic is just above the Ka band allocation. And, Ka band is tested with an oscillator frequency of 2645 MHz — the fourth harmonic is too high for X band, the ninth harmonic is just below the K band allocation and the thirteenth harmonic is just within the police radar Ka band allocation. These numbers are summarized in Table 1.

We now come to the problem of circuit implementation. Figure 6 shows the final schematic. Notice that the final product has three push buttons, one to activate each band. Tuning is accomplished by adjusting a potentiometer to properly bias a varactor for each of the three frequencies. And since the etched microstrip antenna need only radiate signals in the rather narrow 2.625-2.675 GHz range, not their harmonics, its bandwidth is not a problem.

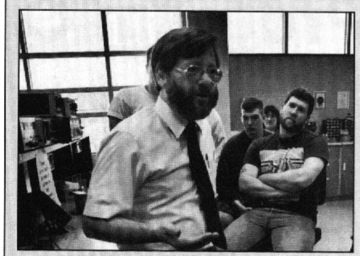
Of course, the input circuit of the radar receiver is a waveguide beyond cutoff, as far as the test signal is concerned. Its loss at 2.6 GHz can be predicted, and compensated for in the link budget. Path loss is fortunately minimal, since: 1) we expect the RadaRanger to be held close to the input of the receiver, and 2) it is an S band signal, rather than X, K or Ka band signals, which must be radiated. Link analysis and bench testing confirm that a 1 mW oscillator near 2.65 GHz will generate internal to the receiver, at a range of 12 cm, ample fourth, ninth and thirteenth harmonics to readily trigger a typical multiband radar detector in all three bands.

The chief problem associated with the original radiated comb solution to multiband radar receiver testing is its spectral inefficiency. In order to test a receiver at three discrete frequencies, it was necessary to generate a comb of not less than 23 separate frequency components. Obviously, FCC Part 15 radiation testing was something of a problem. But by generating a single, spectrally pure RF signal and generating harmonics in the input circuit of the receiver under test, FCC radiation compliance is virtually assured.

By the time you read this, the design concept presented in this article will be available for commercial licensing. Please contact the author or the patent assignee, listed in Reference 1. ***RF***

References

1. RWB Electronics Inc., Box 922, Bronxville, NY 10708; (914) 779-0607.
2. After the Second World War, the last two frequencies evolved into the current 50-54 and 144-148 MHz bands.
3. *Pulse and Waveform Generation with Step Recovery Diodes*, Application Note 918, Hewlett-Packard Co., 1986.
4. *Step Recovery Diode Doubler*, Application Note 989, Hewlett-Packard Co., 1982.
5. *MagIC Low Noise Amplifiers*, Application Note AN-S012, Avantek Inc., 1990.
6. *MGA-64135 GaAs MMIC*, Application Note AN-G003, Avantek Inc., 1990.
7. Al Ward, "Weak Signal Source for 2, 3, 5 and 10 GHz," *Proceedings of Microwave Update '92* , American Radio Relay League 1992, pp. 55-56.
8. Paul Wade, "Mixers, etc. for 5760 MHz," *Proceedings of Microwave Update '92*, American Radio Relay League 1992, pp. 71-79.
9. Ray Waugh, Hewlett-Packard applications engineer, personal conversation, November 1992.



About the Author

H. Paul Shuch is an aerospace engineer and educator, with a Ph.D. in Engineering from the University of California, Berkeley. He is Professor of Electronics at the Pennsylvania College of Technology, One College Avenue, Williamsport, PA 17701-5799. He is credited with designing the first commercial home satellite TV receiver, and holds a patent on the BiDCAS aircraft collision avoidance system. (Photo courtesy Pennsylvania College of Technology)