low-cost microwave spectrum analyzer

How to put together a microwave spectrum analyzer from surplus odds and ends — the completed unit covers dc to 2 GHz

My ongoing efforts to develop low-cost modules for the 1296-MHz band have often required the use of a spectrum analyzer for monitoring (and minimizing) harmonic and spurious frequency components. Numerous excursions through the local surplus test equipment emporiums revealed that an acceptable instrument could cost several thousand dollars — well beyond the budget of the most dedicated experimenter. While searching for the unbeatable surplus buy which never materialized, I noticed the ready availability and comparatively low cost of a wide variety of S-band (2-4 GHz) test instruments and components. It occurred to me that a microwave spectrum analyzer could be put together from these available parts at a considerable savings. This article documents the design, construction, operation, and performance limitations of the resulting microwave spectrum analyzer. While I doubt that any reader will want to duplicate my design in its entirety, I hope this article will provide guidance and encouragement to anyone attempting a similar project.

performance requirements

The operation of any spectrum analyzer can be characterized in terms of its frequency coverage, dispersion, dynamic range, sensitivity, and resolution. To display frequency components well into the microwave region, I designed my spectrum analyzer to cover dc to at least 2 GHz. The same design strategy could be easily applied to other frequency bands. In fact, the upper frequency limit of this analyzer was later extended to 2.5 GHz, as discussed later.

Dispersion describes the ability of a spectrum analyzer to display a broad slice of the frequency spectrum in a single sweep. Many of the low-cost analyzers on the surplus market display only a few MHz at a time. Such narrow-dispersion spectrum analyzers are useful as panadaptors, which display all signals within several hundred kHz of a specified operating frequency, but when tuning a microwave local-oscillator chain, monitoring mixer image response, or measuring transmitter harmonic content, it is often desirable to display a band several hundred (or even thousand) MHz wide. The spectrum analyzer shown here can display the spectrum from dc to 2 GHz in a single sweep. Since it's often desirable to narrow this sweep for a closer look at a particular signal, variable dispersion capabilities are included in the design.

Sensitivity and dynamic range define the minimum and maximum signal amplitudes which an analyzer can display without distortion. In accordance with good engineering practice, I try to suppress all transmitted spurious products by 50 dB or more. To accurately measure this performance, the spectrum analyzer requires at least 50 dB of dynamic range. As

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for maximum input level, I often want to display a + 10 dBm (10 mW) signal (this is the local-oscillator injection level required of many balanced mixers). Thus, 50 dB dynamic range with a + 10 dBm maximum input level yields an ultimate sensitivity requirement of − 40 dBm, or 0.1 μW. Greater sensitivity (a lower minimum discernible signal) could have been obtained, but only at the expense of dynamic range.

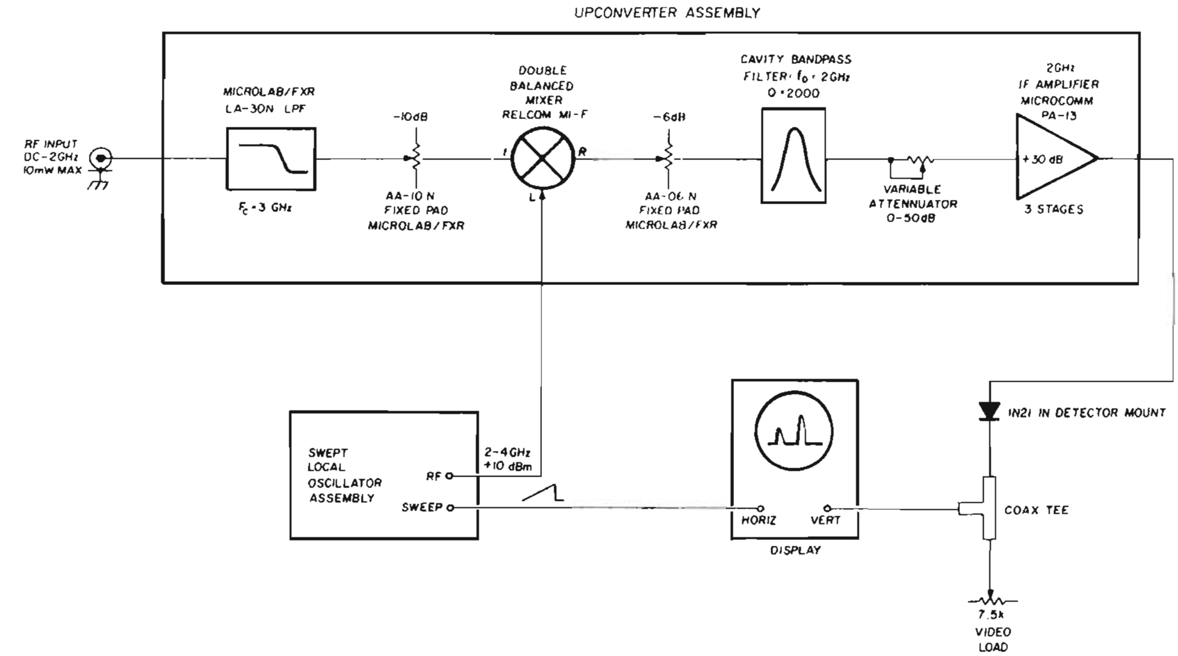


fig. 1. Block diagram of the microwave spectrum analyzer. Most components were purchased on the surplus market. The swept local oscillator, the key to the analyzer, is a surplus 2-4 GHz backward-wave oscillator. The display is an ordinary oscilloscope with dc coupling and provisions for external sweep.

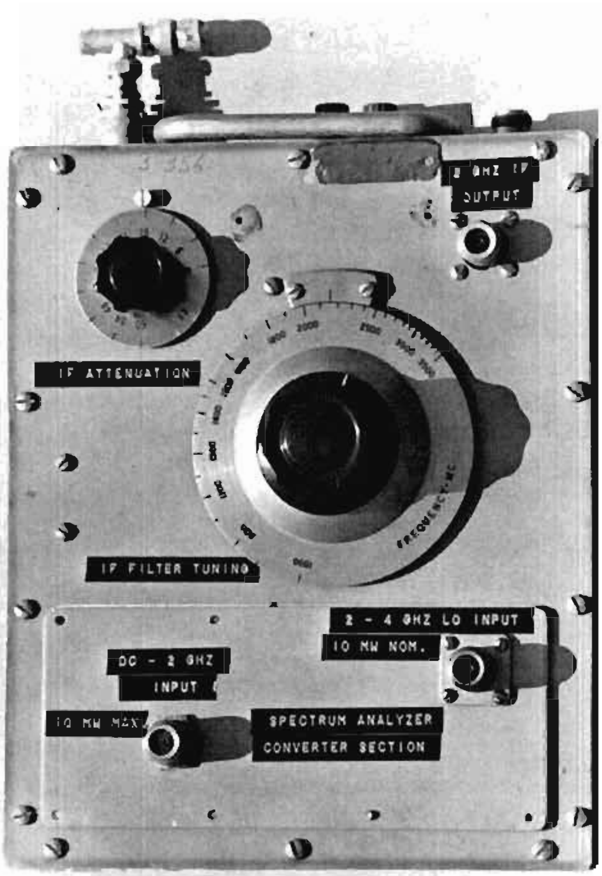
The objective of any spectrum analyzer is to display the various components of a complex waveform in the frequency domain. The closer the frequencies of any two components, the more difficult it is to separate them on the spectral display. Resolution relates to the minimum frequency separation between two signals of equal amplitude which will still permit the operator to discern two separate frequency components on the display.

Resolution can be approximated as twice the i-f bandwidth of the analyzer system. Generally, the objectives of wide dispersion and narrow resolution are mutually exclusive. When measuring transmitter audio intermodulation products with a two-tone test, for example, a resolution of a few hundred Hz is required, and dispersion is likely to be several tens of kHz. When viewing harmonics of a 100-MHz oscillator, on the other hand, 2-GHz dispersion may be required, but a resolution of several tens of MHz is acceptable.

Resolution is primarily a function of i-f bandwidth, which for my analyzer is fixed at 1 MHz. Therefore, with this design, I can resolve frequency components to within about 2 MHz.

As most amateurs know, a general-coverage communications receiver can be used as a rudimentary high-frequency spectrum analyzer. With an input signal applied to the antenna terminals, the receiver is manually tuned through its frequency range (dispersion). Frequency components are detected and displayed (perhaps with the receiver's S-meter). Resolution is a function of the i-f bandwidth, which is probably a few kHz. Sensitivity is a function of the receiver's noise floor, and dynamic range is limited by the receiver's agc and overload characteristics. Obviously, wide dispersion measurements require considerable operator intervention, in the form of tuning. Gain variations of the receiver from band to band will limit the accuracy of its amplitude indication. Additionally, any nonlinearity in the receiver's agc circuit may prevent accurate amplitude measurement across the receiver's entire dynamic range. Also, the receiver's image and spurious rejection may be insufficient to eliminate false indications.

Ideally, a workable spectrum analyzer should be a superheterodyne receiver in which these shortcomings are minimized. Frequency tuning should be both automatic and rapid. Instead of an S-meter, amplitude is displayed on an oscilloscope. If the scope's horizontal deflection is slaved to the receiver's tuning mechanism, the result is a display in the frequency domain. Dynamic range must be max-



Front panel of the microwave spectrum analyzer showing the operating controls. The variable i-f attenuator (upper left), although calibrated in 6 dB steps, permits amplitude comparison of signals displayed on the oscilloscope. The i-f bandpass filter (center) sets the frequency coverage of the analyzer, as discussed in the text.

imized, and spurious/image responses eliminated, to the greatest possible extent.

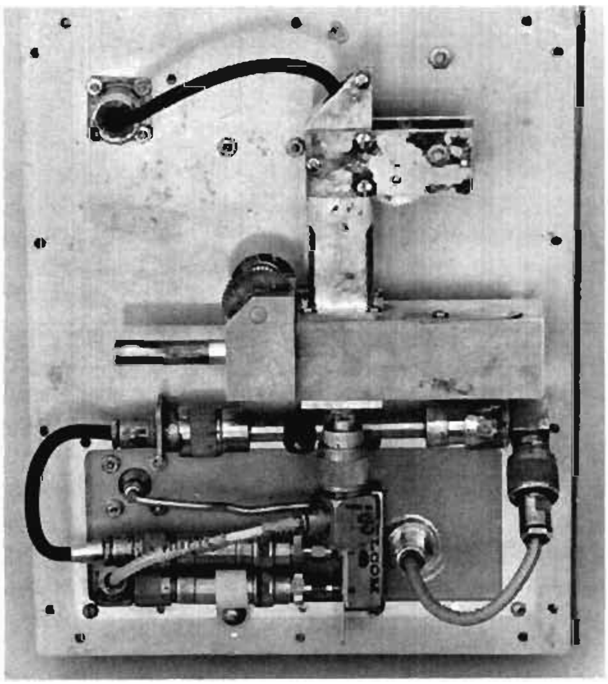
Many of the objectives discussed previously are met in the design shown in **fig. 1**, a wide dynamic range microwave receiver with an electronically tuned local oscillator and ample image rejection. It includes a 2-GHz i-f amplifier with variable gain and fixed bandwidth, and a sensitive detector for driving an oscilloscope. Unlike conventional receivers, this design up-converts the incoming signal to an i-f in the microwave region. Although this approach complicates i-f design, it permits wide dispersion tuning. It also improves separation of the rf and image signals so a simple lowpass filter can be used to eliminate image responses.

The microwave spectrum analyzer is divided into three separate sub-systems: the local oscillator, unity-gain upconverter, and display sections.

local oscillator

Central to the design of this spectrum analyzer was the availability, on the surplus market, of a leveled, swept signal source covering 2 to 4 GHz. I used an Alfred 622BK sweep oscillator, but any similar generator should work satisfactorily. These sweep generators consist of a voltage-controlled oscillator, typically a backward wave oscillator or BWO (a microwave oscillator built around a device similar to a traveling wave tube), power supplies, a sawtooth generator for developing a constantly varying vco control voltage, and leveling circuitry to maintain constant output across the band. *Start* and *stop* frequency adjustments permit the oscillator to sweep all, or any portion of, the 2 to 4 GHz band. Leveled output power is typically 10 to 30 milliwatts.

Many companies are currently retiring their BWO sweep generators in favor of wideband, solid-state units, so quite a few BWO generators have recently appeared on the surplus market at prices ranging from $200 to $400 or so. Since this is the most costly component of the microwave spectrum analyzer, make sure the unit you buy is in good operating condition. Reputable electronics surplus dealers will often let you power up an instrument and make a few measurements prior to purchase. A practical test requires the use of a microwave power meter (bolometer bridge or equivalent) to observe output power in the leveled CW mode as the generator is manually tuned across the band. Although a few dB variation is acceptable, dead spots or severe power drop-off at the high end of the band indicates a failing BWO. A good, used BWO should provide years of reliable life in intermittent amateur service.



Interior of the spectrum analyzer converter section showing the double-balanced mixer and attenuation pads, input filter, i-f filter, and variable i-f attenuator.

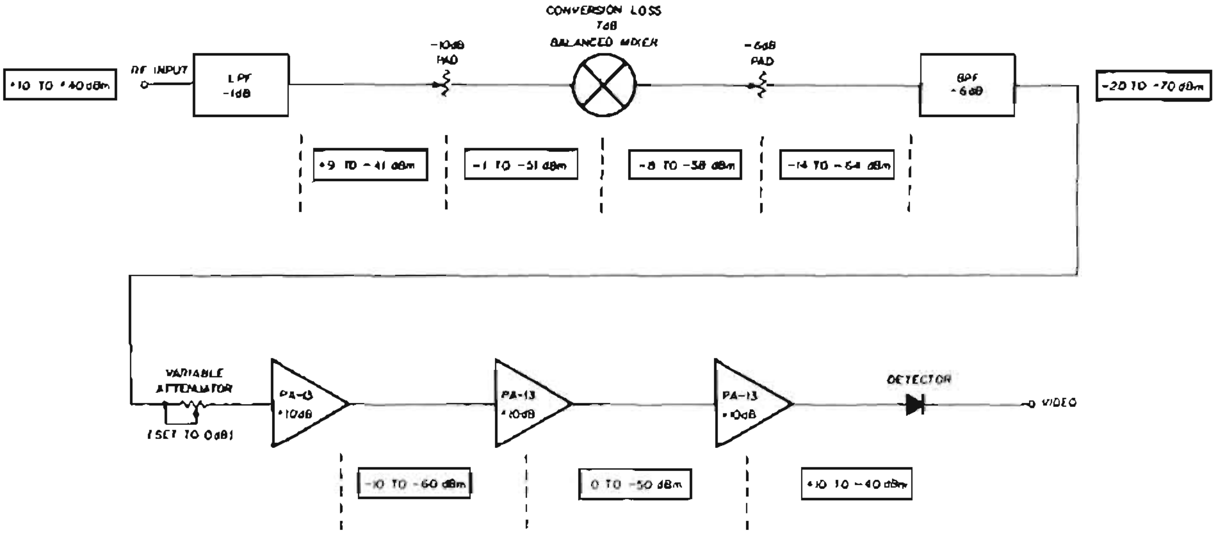


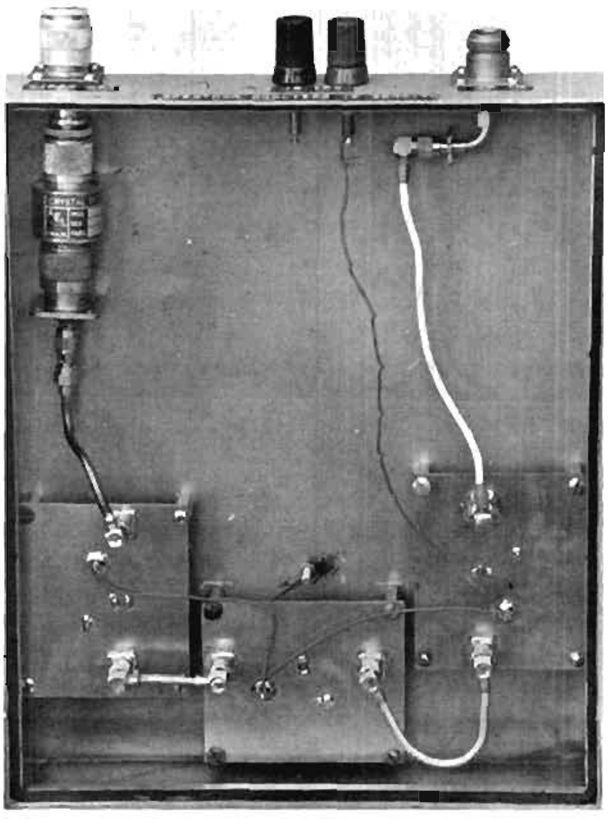
fig. 2. Power levels in the upconverter used with the microwave spectrum analyzer (with the variable attenuator set at 0 dB, which results in unity conversion gain).

As can be seen in the block diagram, **fig. 1**, the spectrum analyzer converter assembly consists of an input lowpass filter, an S-band double-balanced mixer, some attenuator pads, a high-Q i-f filter, a variable i-f attenuator, and sufficient i-f amplification to bring maximum conversion gain to unity. The i-f detector and its video load, though installed in the converter assembly, are discussed later with the display.

The characteristics of the balanced mixer, more than any other component, establish the linearity and dynamic range of the analyzer. I used a Relcom M1F mixer which I found on the surplus market for $35 (the mixer retails for about $200). The rated frequency response of this mixer is dc-2 GHz at the i-f port, and 2-4 GHz at the rf and LO ports. Note that the incoming signal is applied to the *i-f port*; the *rf port* drives the i-f system. Thus, all ports are operated withinn their specified frequency ranges.

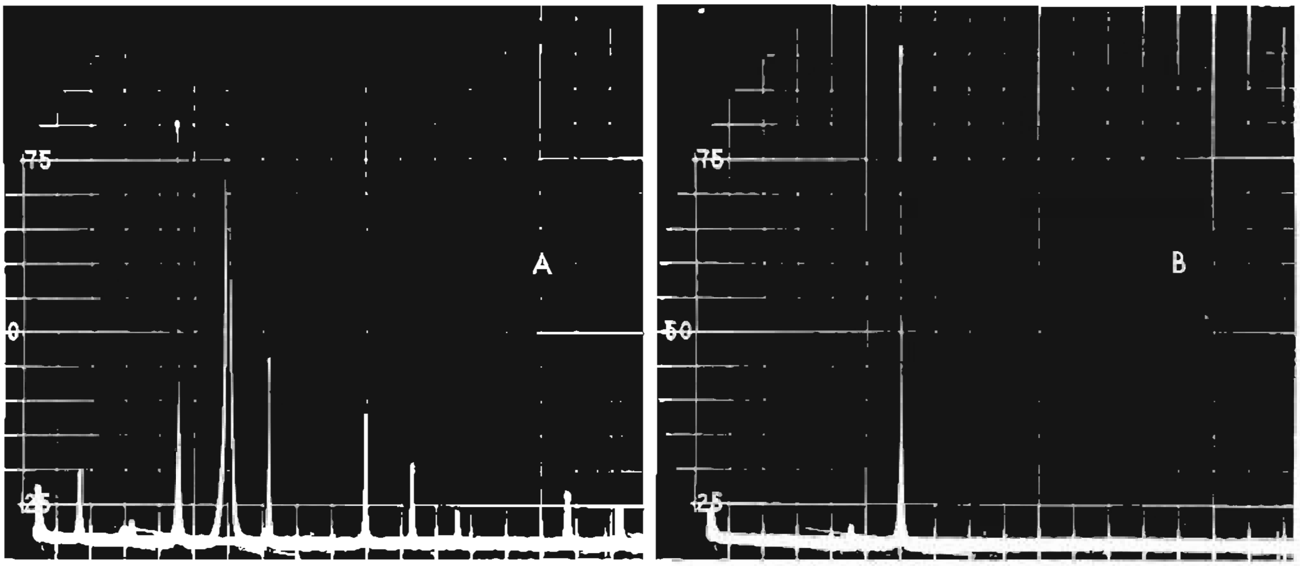
With the 10 mW of local-oscillator injection applied to the mixer from the sweep generator, the mixer's conversion efficiency is compressed by 1 dB at an input signal level of 1 mW. Since I wanted to analyze a 10 mW signal on the spectrum analyzer without exceeding 1 dB compression, it was necessary to place a 10 dB attenuation pad ahead of the mixer's input (i-f port). This pad also assures proper impedance termination for the mixer, as does the 6 dB attenuator at the output (rf port). Fixed attenuators for dc to 2 GHz are available to the surplus bargain hunter for as little as $5.00, or may be purchased new for $15 to $20.

With 2 GHz i-f, and a swept LO covering 2 to 4 GHz, the mixer will respond to signals in the dc-2 GHz region, as well as in the 4-6 GHz image band. Any components in the image band will cause considerable confusion on the display. Thus an input lowpass filter was installed in the system to block all signals above 3 GHz from entering the mixer. I used a Microlab/FXR LA-30N filter which I salvaged from another piece of equipment. Although the filter originally cost $40, similar devices are available through surplus outlets for $5 to $10.



Spectrum analyzer i-f section. The three 2-GHz amplifiers are at the bottom. Diode detector is at upper left.

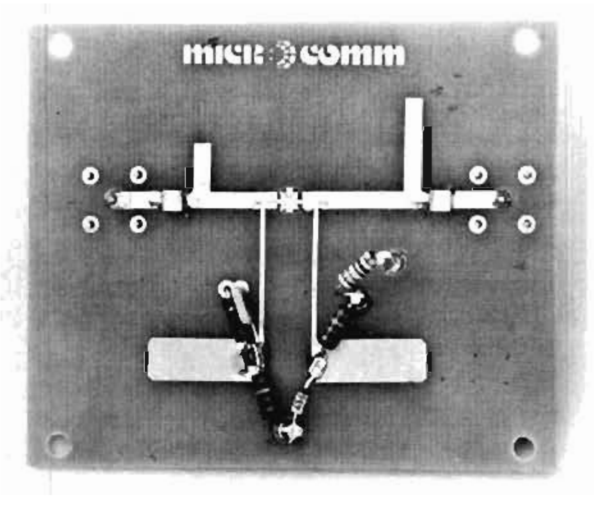
The i-f bandwidth of this analyzer is established by a high-Q tunable coaxial or cavity filter which is tuned to 2 GHz. I used the filter from a surplus TS-406 noise generator, but any cavity with a Q of 1000 or greater should be acceptable. It's also possible to use filter to vary i-f gain. The attenuator I used was also salvaged from the TS-406 noise generator, but any continuously variable or step attenuator rated to 2 GHz is acceptable — 10 dB steps will allow coarse system gain control; if 1 dB resolution is included,



Example of spectral impurity, as displayed on the microwave spectrum analyzer. Presence of harmonic, subharmonic, and spurious signals shown in *A* is the result of an overdriven uhf amplifier. The same amplifier, with drive reduced to the rated level, is shown at *B*: the one spurious component is down by more than 20 dB. Display is from dc to 2 GHz.

a *transmission-mode* cavity wavemeter as an i-f filter. These widely available devices have a loaded Q of several thousand, and exhibit only a few dB of insertion loss at resonance. Note that an absorption-type wavemeter is *not acceptable* because the filter must pass maximum signal to the i-f amplifiers at resonance.

A 50 dB variable attenuator was installed after the



Microstripline side of the 2-GHz amplifier (Microcomm PA-13). Three of these units provide 30 dB gain at 2 GHz.

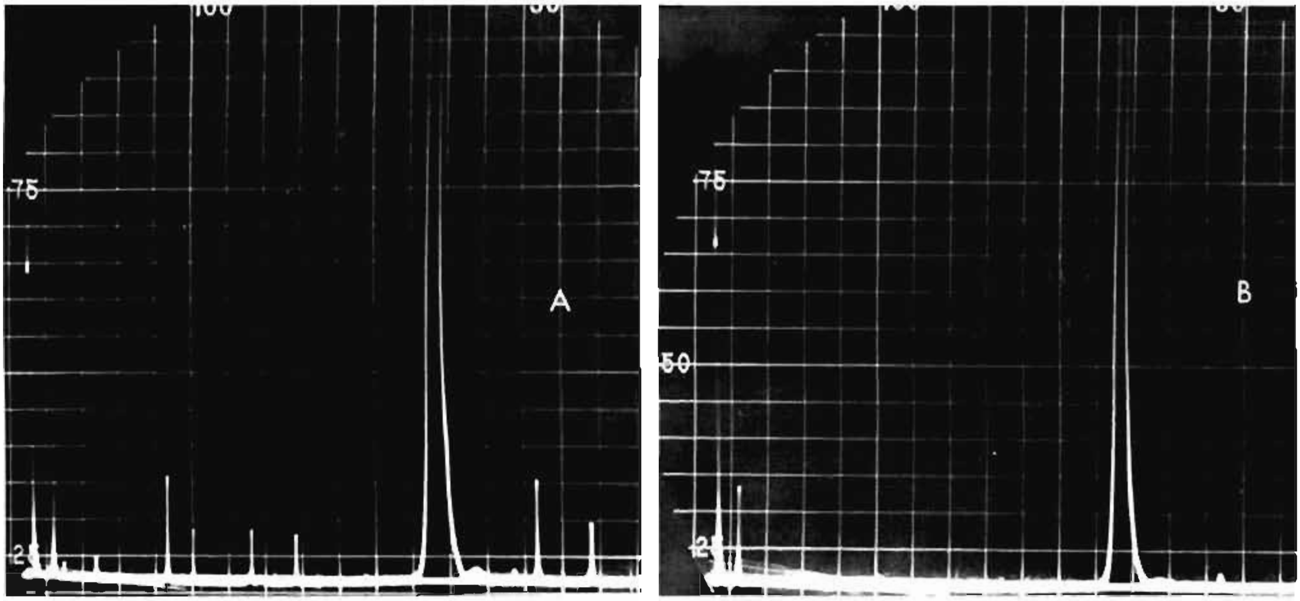
the attenuator can also be used for accurate signal level comparison. This is accomplished by viewing one signal component, setting a convenient reference level on the display, varying the attenuator for a like indication on the other signal component, and noting the change in attenuator settings.

Considerable i-f gain is required to achieve the desired sensitivity. I cascaded three stages of the Microcomm PA-13 buffer amplifier.* These microstripline amplifier modules offer 10 dB of gain per stage across the 2.0-2.3 GHz band, and are biased for 30 mW output at 1 dB gain compression. Since i-f noise figure is not a limiting factor so far as system sensitivity is concerned, any available wide dynamic range amplifier for 2 GHz may be used.

display

The local-oscillator signal for the spectrum analyzer is swept by a sawtooth waveform; therefore, displaying a signal in the frequency domain is simply a matter of detecting the output signal from the i-f amplifiers, applying the recovered video to the vertical deflection amplifier of an oscilloscope, and applying the sawtooth output voltage from the sweep generator to the oscilloscope's horizontal axis. Since a relatively slow sweep rate is used, the

*Available for $64.95 per stage (plus postage and handling) from Microcomm, 14908 Sandy Lane, San Jose, California 95124.



Output of a local-oscillator chain for a 1296-MHz converter. At *A* the i-f gain of the spectrum analyzer has been increased to show the spurious signals, which are 30 dB below the desired signal. The display at *B* shows the output of the same local oscillator after it has passed through a 3-pole bandpass filter. Although the filter has attenuated the desired signal by 1 dB, all spurious signals are down more than 50 dB.

frequency response of the oscilloscope is unimportant. Virtually any scope with dc coupling and provisions for external sweep may be used.

The dynamic range of the detector which follows the i-f amplifiers is of major concern. **Fig. 2** shows the nominal gain or loss of each element of the analyzer upconverter, as well as maximum and minimum signal levels present at each stage with zero i-f attenuation (maximum sensitivity). Since the upconverter is operated at unity gain, the power available to the detector will vary from +10 to −40 dBm. Thus the diode's tangential sensitivity must be considerably below −40 dBm, and the diode's saturation point above +10 dBm, for a usable display. Although I know of no diode whose transfer characteristics are uniform over so wide a range, the 1N21 family of point-contact diodes are acceptable within certain limitations (discussed later).

Diode dynamic range is enhanced by the optimum terminating impedance, which may vary between 1000 ohms and 10 kilohms or so. The input impedance of an oscilloscope's vertical deflection amplifier is typically 1 megohm; thus, to assure proper termination for the diode, a loading resistor is required, as shown in fig. 1. Since terminating the diode's video port degrades the amplitude of the recovered video, increased oscilloscope vertical sensitivity is required. On my analyzer, a 7.5k ohm video load, in conjunction with a vertical sensitivity of 10 mV/cm, provides an acceptable display.

Note that the vertical display of the spectrum analyzer is approximately linear, not logarithmic. Therefore, it is possible to view only about 25 dB of amplitude range at once, and only with extremely limited amplitude resolution. However, by using the i-f attenuator to establish reference levels as described previously, the entire 50 dB of usable

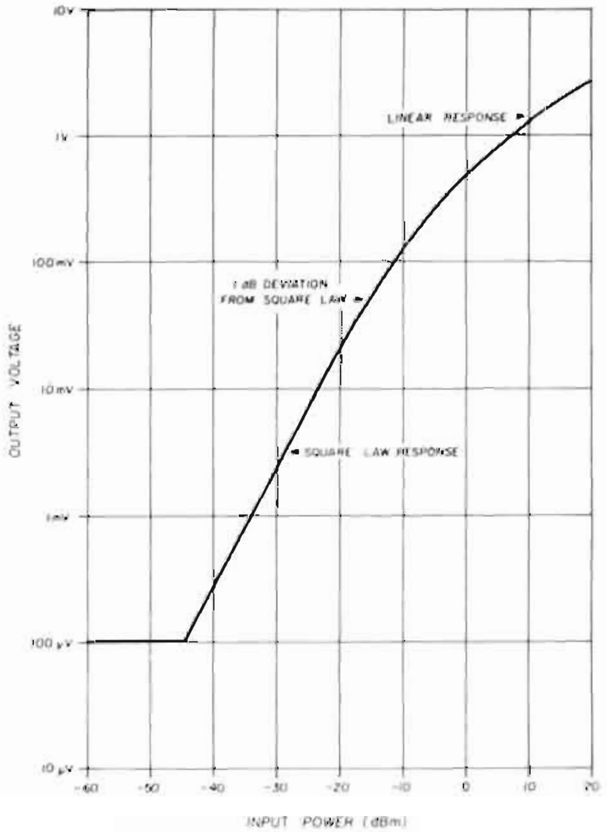


fig. 3. Transfer characteristics of a typical microwave diode detector using a point-contact diode.

dynamic range can be put to use. Future plans include capability for a logarithmic display, as outlined toward the end of this article.

I built the entire upconverter module in the case of a surplus noise generator (the filter and attenuator of which formed key i-f elements in my system). As can be seen in the photographs, the i-f amplifiers are mounted on standoffs inside the main chassis, and connected with UT-141 semi-rigid coaxial cable. If flexible coax is used, I recommend RG-142B/U. This ¼-inch (6.5mm) cable is double-shielded, silver plated, has a Teflon dielectric, and accepts clamp-type SMA plugs of the low-cost E. F. Johnson JCM series.

If desired, the i-f amplifiers may be mounted in Pomona 3601 die-cast aluminum boxes. These boxes present a neat appearance and afford somewhat better shielding than the standoff approach I used.

The various components of the upconverter assembly sport a variety of connectors; between-series adapters are required to interface types N, SMA, and TNC receptacles.

operation and applications

A recent article discussed a variety of spectrum analyzer applications of interest to amateurs.[1] For additional information, Hewlett-Packard has published two application notes which discuss both the procedures and the theory of spectrum analysis.[2,3]

The accompanying photographs show the displays obtained with this analyzer when measuring LO harmonic content, balanced mixer carrier rejection, converter image response, and transmitter intermodulation products.

improving sensitivity

One of my primary design objectives was the ability of the analyzer to handle relatively large (+10 dBm) input signals without overloading. The input pad shown in **fig. 1**, although it prevents mixer overload at these signal levels, obviously limits the ultimate sensitivity of the system. Additional i-f amplification would enhance the ability of the analyzer to display very small signals — but then the detector diode would saturate at high input signals.

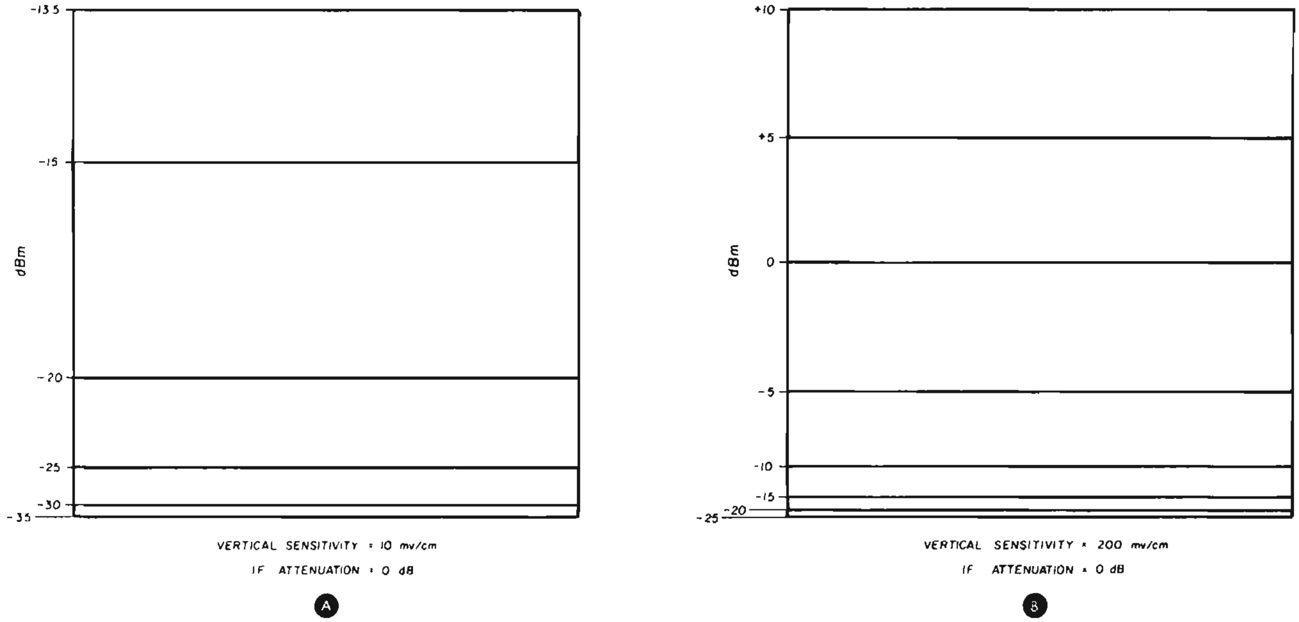
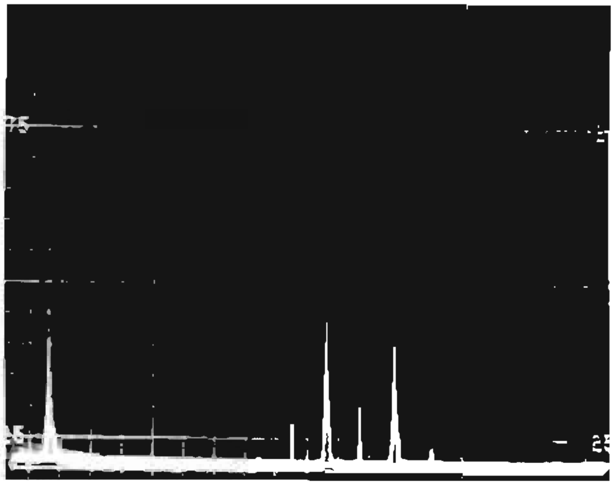


fig. 4. Approximate vertical scale calibration of the analyzer display (no video processing). Note the excellent linearity at high power levels, and the compressed display when the detector diode is operated in the square-law region.

Where both increased sensitivity and large-signal handling capability are required, it's necessary to replace the 10 dB input pad with an appropriate step attenuator (and possibly adding additional i-f stages). One candidate for the input attenuator is the Kay 520 which offers 10 dB steps to 70 dB and is flat to 2 GHz. This unit is priced under $100, but like everything else in my spectrum analyzer, units are often available through surplus sources at considerable savings.

Note that no variation in input attenuation or i-f gain can increase the dynamic range of this analyzer beyond 50 dB or so. Therefore, it is essential that the operator select input attenuation which is appropriate for the anticipated signal level. In short, input attenuation should be such that the signal applied to the mixer does not exceed 1 mW, and that to the detector remains below 30 mW. A simple operating check involves increasing the input at-



As a transmitting mixer's i-f port is overdriven, intermodulation products at *LO ± 2i-f* become more pronounced, and the amplitude of signals at *LO ± 3i-f* begins to increase. This display also shows the second harmonic of the i-f injection signal (at the left).

tenuation by 10 dB while decreasing i-f attenuation by the same amount. An increase in the apparent amplitude of the displayed signal indicates that the mixer was being over-driven.

expanding frequency coverage

Recently I became involved in designing amplifier, mixer and LO modules for 2304 MHz, and wanted to extend the upper frequency limit of this spectrum analyzer. This could be accomplished by varying either the swept LO frequency or the i-f frequency, or both. Since the LO frequency range is limited by the coverage of the available sweep generator, I chose to change the i-f frequency.

With a 2 to 4 GHz swept LO, frequency coverage from 500 MHz to 2.5 GHz could be obtained by modifying the analyzer's i-f to 1.5 GHz. However, this exceeds the rated frequency range of the mixer's rf and i-f ports. Fortunately, the frequency response of the i-f port of the mixer I used exceeded the specified 2 GHz. At 2.5 GHz input, vswr is degraded somewhat, but the use of the 10 dB input pad effectively masks this mismatch. As for the frequency response of the mixer's rf port (used to develop i-f output), reducing the i-f frequency to 1.5 GHz degrades conversion efficiency by several dB. The i-f is fixed, however, so this degradation applies equally to all input signals, and no system linearity is sacrificed.

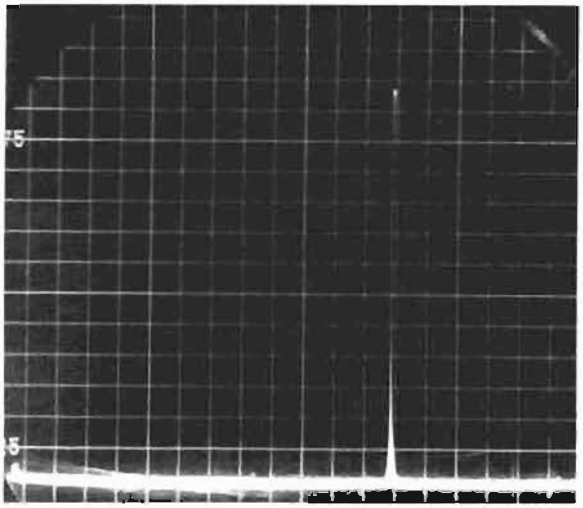
I originally planned to switch in a separate i-f system for high band (0.5-2.5 GHz) coverage, but I discovered that the PA-13 i-f amplifiers were sufficiently broadband that they have usable gain at 1.5 GHz. Since the cavity filter used to establish i-f bandwidth is tunable, setting the spectrum analyzer up for high-band coverage is simply a matter of retuning the i-f filter to 1.5 GHz. In this mode, overall analyzer sensitivity is degraded by about 10 dB, but it is still adequate for many applications.

With a 1.5 GHz i-f, the input signal range extends from 500 MHz to 2.5 GHz, and the image band from 3.5 to 5.5 GHz; therefore, the existing 3-GHz lowpass filter provides ample image rejection without degrading input frequency coverage.

detector limitations

In normal operation (**fig. 2**) the diode detector sees a power level from −40 to +10 dBm. **Fig. 3** shows the transfer characteristics of a typical microwave detector diode over this range. It can be seen that the diode is being driven from its square-law region into its linear region. Thus, at high signal levels, 10 dB of signal change results in approximately a 10 dB change in recovered video amplitude; at lower power levels a 10 dB input signal variation may change video amplitude by up to 20 dB. Obviously, the linearity of the display is marginal, at best, and usable dynamic range is restricted to about 25 dB unless the operator varies i-f gain, or vertical sensitivity or both.

Hewlett-Packard introduced a series of oscilloscope overlays for interpreting non-linear



Properly driven 1296-MHz transmit mixer, at the output of a 3-pole bandpass filter. The image, i-f, and LO signals are all 40 dB down; intermodulation products are more than 50 dB down. The small pip at the left side of the trace is the bandedge marker and represents zero frequency; it is produced when the LO sweeps through the i-f filter.

(more properly, non-logarithmic) swept displays.[4] A similar set of overlays, which I have derived for my spectrum analyzer, is shown in **fig. 4**. Although this calibration data is valid only for my analyzer, a similar vertical axis can be derived for any spectrum display. All you have to do is apply an input signal of known amplitude through an accurate step attenuator. By varying the attenuation and noting the displayed amplitude, calibration lines can be grease-penciled directly on to the face of the CRT.

The utility of this spectrum analyzer would be greatly enhanced if it were possible to display simultaneously all signals between −40 and +10 dBm. If you want to view the entire 50 dB dynamic range without adjusting reference levels with the i-f attenuator or varying vertical sensitivity, it will be necessary to apply the output of the detector into a compression video amplifier.

There are several integrated circuits available which provide logarithmic video amplification; with a logarithmic amplifier a display such as that shown in **fig. 5** can be obtained. Note that below about −10 dBm, the display approaches a uniform 5 dB per centimeter deflection. However, the transition from square-law to linear detection results in severe scale compression at higher power levels.

An ideal spectrum analyzer display should have vertical response similar to that shown in **fig. 6**. Although I have not yet been able to achieve this performance, it should be possible by developing a logarithmic video amplifier which makes its transition to linear response above a selected input level.

An approach used successfully by Pacific Measurements in their logarithmic power meters involves an operational amplifier in which the feedback resistance is a nonlinear element (a semiconductor junction). As the junction potential of this feedback path is exceeded, the gain curve of the op amp changes. The result is an amplifier which makes its transition from logarithmic to linear response at selected power level. Perhaps some reader will be able to contribute a similar circuit for appropriately shaping the video output of the spectrum analyzer's diode detector. What is needed is a display whose

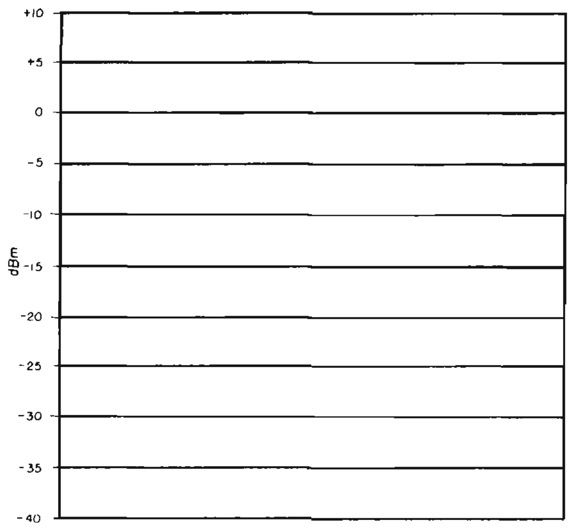


fig. 6. Ideal vertical response for a spectrum analyzer. This response requires a video amplifier with a logarithmic compression curve below an input of 200 mV, and linear response above 400 mV.

amplitude is graduated at 5 dB per centimeter, over the entire dynamic range of the system. This modification would significantly enhance both measurement accuracy and ease of operation.

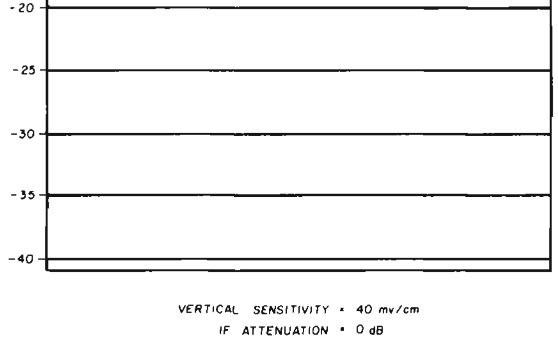


fig. 5. Typical vertical scale calibration of a spectrum analyzer with a logarithmic video amplifier. In this case display linearity is good at lower input signal levels, but compresses rapidly as the detector diode enters the linear region.

acknowledgements

Thanks are in order to Nick Marshall, W6OLO, for first encouraging me to try to build my own spectrum analyzer, and to Richard Chatelain, WB6JPY, who took the photographs. I must also acknowledge the eager support of my wife, WA6PLF. She reasoned that, if I built my own analyzer rather than spending funds I didn't have to buy one I couldn't afford, we would make good use of the money we saved. Although I'm not sure I understand the economics, I'm enjoying both the homebrew spectrum analyzer and our new car.

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2. *Spectrum Analysis*, Application Note 63, Hewlett-Packard, 1501 Page Mill Road, Palo Alto, California, May, 1965.
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