TABLE II
PARAMETER VALUES FOR FIFTH-ORDER TRIAL FOLDED-LINE BANDSTOP FILTER

Line Number	Self-Capacitance Normalized to $376.7/\sqrt{\epsilon_r}$ C_{g_i}/ϵ and $C_{g_{4-i}}/\epsilon$	Mutual Capacitance Normalized to $376.7/\sqrt{\epsilon_r}$ $C_{i,i+1}/\epsilon$ and $C_{3-i,4-i}/\epsilon$	Theoretical Stub Normalized to Terminating Admittance	Coupling Capacitance (80Ω Stub)
1	0.7052	0.1121	0.1464	0.93pF
2	0.5423		0.1464	0.93pF

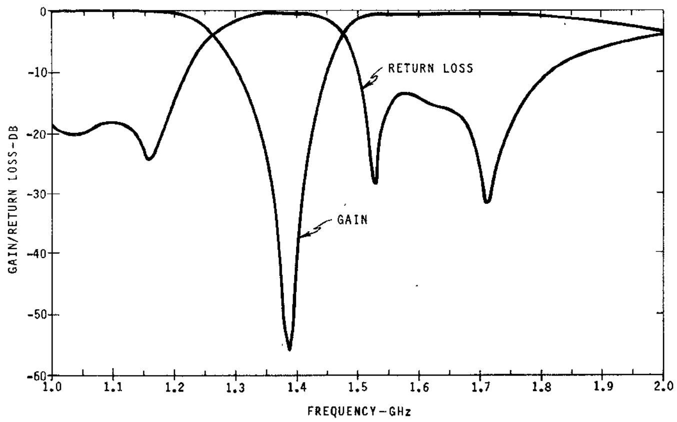

Fig. 9. Measured responses of a fifth-degree folded-line bandstop filter with capacitive-coupled half-wave stubs.

The nominal center frequency was chosen to be 1.4 GHz. Filter parameter values are summarized in Table II. The filter was tuned in the manner previously described, resulting in the measured responses given in Fig. 9. Optimum tuning was accomplished slightly below 1.4 GHz, presumably because the added length of the turns between lines was not accounted for in the stripline realization. The measured fractional bandwidth was approximately 0.24 which compares favorably with the expected value of 0.25. In fact, a comparison of the computed data of Fig. 8 and measured data of Fig. 9 shows generally excellent agreement between them.

CONCLUSIONS

Design tables for folded-line bandstop filters of fifth and ninth degrees and a 0.1-dB passband ripple were compiled for a range of bandwidths. Folded-line bandstop filters have greater selectivity than their linear-geometry counterparts of the same degree. The increased selectivity is small for narrow bandwidths but appreciable for wide bandwidths. Experimental results on two trial folded-line filters confirmed the designs and feasibility of the filter geometry. Folded-line and hybrid geometries together with linear geometries will give the filter designer increased flexibility in selecting stripline and MIC realizations.

ACKNOWLEDGMENT

The authors wish to thank Dr. C. K. Campbell for the use of his laboratory facilities and G. Kappel for drafting a number of the figures used in this short paper.

REFERENCES

[1] P. I. Richards, "Resistor-transmission-line circuits," *Proc. IRE*, vol. 36, pp. 217–220, Feb. 1948.
[2] E. G. Cristal, "Meander-line and hybrid meander-line transformers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 69–76, Feb. 1973.
[3] E. G. Cristal and U. H. Gysel, "A compact channel-dropping filter for stripline and microwave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 499–504, May 1974.
[4] R. Sato, "A design method for meander-line networks using equivalent circuit transformations," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 431–442, May 1971.
[5] H. Ozaki and J. Ishii, "Synthesis of transmission-line networks and the design of UHF filters," *IRE Trans. Circuit Theory*, vol. CT-2, pp. 325–336, Dec. 1955.
[6] W. J. Getsinger, "Coupled rectangular bars between parallel plates," *IRE Trans. Microwave Theory Tech.*, vol. MTT-10, pp. 65–72, Jan. 1962.

An Automated General Purpose Test System for Solid-State Oscillators

JOHN R. HUMPHREY, MEMBER, IEEE

***Abstract*—An automatic test system for determination of the tuning and output characteristics of voltage-controlled solid-state oscillators is described. Hardware, software, and functional capabilities of the broad-band modular system are presented. The utilization of a minicomputer for data collection with on-line curve fit and rapid CRT display of test and analysis results facilitates device tuning and streamlines traditionally tedious measurement tasks.**

I. INTRODUCTION

There exist numerous measurement problems associated with the medium scale production of today's microwave systems which demand consideration in terms of test automation. The demand is economic in nature, for automation can improve both people and asset effectiveness.

Current technology supports microwave measurement automation in two ways. Complete general purpose network analyzers equipped to solve a wide class of problems such as broad-band measurement of S parameters are available [1]–[3]. However, there are many measurement requirements not covered by one of such proffered general purpose machines. For some of these problems there are programmable instrumentation components available which when innovatively integrated may constitute a test system of sufficient power to justify development costs [4].

The decision to "custom automate" has been a gamble of sorts because effort estimates are often difficult and results may not smoothly fulfill expectation and need. However, careful planning with a wary eye on modularity, flexibility, and utilization optimization can go far toward ensuring the success of the effort.

II. MANUAL TECHNIQUES—TIME CONSUMING, INEFFICIENT

The system to be described was designed to test solid-state voltage-controlled oscillators (VCO's) which serve as local oscillator (LO) elements in radar and guidance systems. Device types

Manuscript received May 9, 1974; revised July 1, 1974.
The author is with Texas Instruments, Inc., Dallas, Tex. 75222.

include lower frequency VCO's, oscillator/multiplier pairs, and varactor tuned Gunn diode oscillators. Typically, one third to one half of the cost for producing these units is directly attributable to test and tuning requirements. Conventional test techniques are tedious and sometimes inadequate. Tuning tends to be an educated guess proposition rather than a specific process efficiently dictated according to carefully gleaned test results.

Required measurements are similar for all solid-state local oscillator (SSLO) projects. Measurement of the voltage/frequency tuning characteristic is a universal requirement. Conventionally, voltage/frequency data are collected manually on a point-by-point basis or at best on a swept mode basis (with inherent computational limitations) using a counter, D/A converter, and X–Y recorder (or similar setup). Tuning data analysis requirements depend upon the SSLO in question and may be as simple as a calculation of point-to-point incremental slope for a certain minimum number of data points in a specified range. Other devices require precise computer analysis of data for calculation of curve fit parameters and determination of deviation of actual data from best-fit characteristics. Signal power measurements as a function of frequency are also required on all oscillators. Noise measurements are usually required as well.

Consider then the test problem for an average ten SSLO's per month production run for a given radar system. Multiply this by seven projects or more and the result is from 500–1000 h of test time associated with SSLO production per month—a problem worthy of automated test consideration.

III. AN AUTOMATED SOLUTION TO THE SSLO MEASUREMENT PROBLEM

Fig. 1 is a photograph of the computer-controlled test system which was developed for engineering and production SSLO testing. The elements of the system are shown in the simplified block diagram of Fig. 2. The system consists of four distinct subsystems:

1) microwave subsystem;
2) data processing subsystem;
3) stimulus and control subsystem;
4) software subsystem.

Each of these subsystems will be discussed with regard to its components and role in overall system capability.

A. Microwave Subsystem

The microwave subsystem consists of a microwave multiplexer and the measurement instrumentation shown in Fig. 2. The microwave multiplexer includes the test device connection interface and switching circuits. Circuitry is included for frequency, signal, and 60-MHz AM noise power, and spectral measurements, 1–18 GHz. Four test ports each for coax, WR90 waveguide, and WR62 waveguide are provided. Fig. 3 is a block diagram of the *Ku*-band (WR62 waveguide) circuitry of the microwave multiplexer. Nearly identical X band and coaxial networks are provided.

Multiple connection capability precludes test system idleness during periods when one or more SSLO's are temperature soaking in one of the three test set thermal chambers. Inactive SSLO's are switched into matched loads while a single SSLO is enabled to the measurement instrumentation.

Frequency measurement is provided by a broad-band frequency counter with a single input port and minimum sensitivity of -26 dBm. Power measurement is provided by an instrument with frequency coverage of 1–18 GHz with a 50-dB dynamic range. These units employ ASCII and BCD data formats, respectively, and are read on an interrupt basis by the system computer. A broad-band spectrum analyzer with preselector furnishes system spectral measurement capability on a manual or semiautomatic basis—semiautomatic in that the system will provide a continuous tuning voltage sweep over a specified range and at a specified rate. Spectral characteristics are observed and noted by the operator.

In a receiver, the nonlinear action of the mixer translates the LO noise power which happens to be at the signal frequency or at the image frequency to the IF frequency, thus lowering the signal-to-noise ratio (SNR) [5]. The test set includes capability for automatic measurement of 60-MHz AM sideband noise power. This is accomplished by translation of the radar system LO noise figure degradation specification to a noise power level which can be detected with an appropriate receiver and which reflects system bandwidth, noise figure, and mixer cancellation characteristics. A high-gain narrow-band receiver (Fig. 3) is utilized to monitor a noise power level which includes both test system noise power plus LO noise

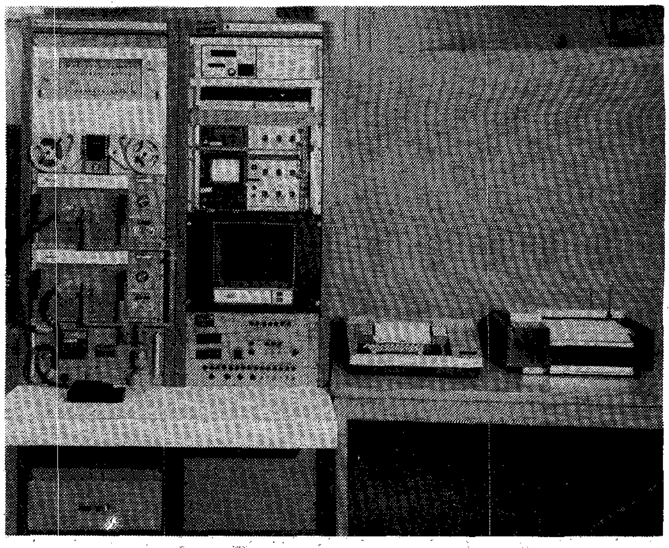

Fig. 1. Photograph of an automatic SSLO T/S built for a government test facility.

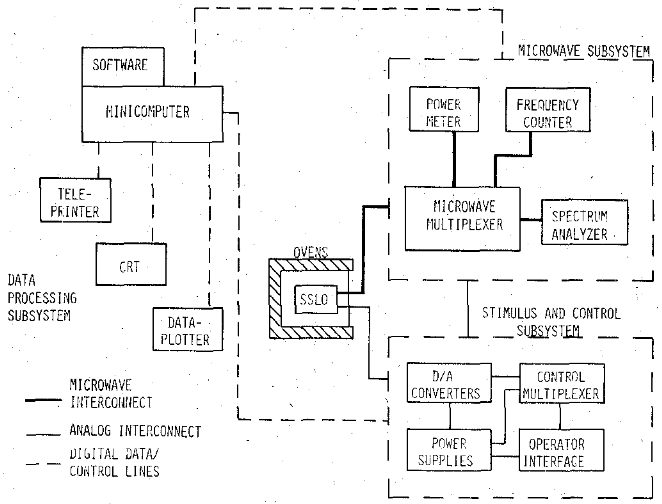

Fig. 2. Block diagram of the SSLO test system.

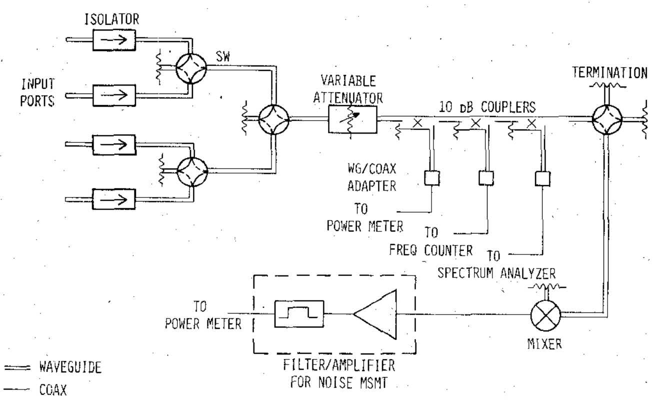

Fig. 3. Block diagram of *Ku*-band microwave circuitry in the microwave multiplexer.

power, if any. A specification limit for this measurement which compensates for test set characteristics has been calculated so that verification of LO adherence to noise specifications can be made. The specification limit typically lies 4 dB or more above the noise power level contributed by the test set.

System calibration is straightforward and is performed periodically at 3-month intervals. A Hewlett-Packard Automatic Network Analyzer is utilized to measure microwave circuit loss factors which are stored and automatically applied to test data. The noise measurement circuitry was carefully calibrated and characterized before installation in the test system. Periodic checks are made to guarantee stability of this circuitry. Standard oscillators which may be tested on other test stations are maintained and tested on the automatic system at regular intervals between calibration cycles. This has proven to be an effective technique for tracking and validating system performance.

B. Data Processing Subsystem

The data processing subsystem consists of the minicomputer which includes 24K words of MOS memory, a storage CRT display, an X–Y plotter, and thermal printer (used for data printing and parameter input/output). The CRT provides rapid display of test and analysis results. All output presented on the CRT is available in hard-copy plot and tabular form via the X–Y plotter and thermal printer, respectively.

C. Stimulus and Control Subsystem

This subsystem includes two D/A converters, power supplies, an AUTO/MANUAL control multiplexer, system interface control panel, and the computer. Two D/A converters are needed to fulfill requirements for single or dual tune line SSLO's. The power supply system serves the switching circuits and logic networks and provides test unit bias voltages. The operator interface is simple in design, largely due to the symmetry of the microwave test multiplexer. Three selections are required to channel a given test port to the measurement instruments when operating in the manual mode. The operator selects BAND, PORT, and RF/NOISE functions. The interface also includes digit switches for manually selecting tuning and dc bias levels. Tuning voltage is variable in 10-mV steps from +10 to −10 V. For tuning requirements outside this range a variable gain amplifier may be included in the device test interface. Provision is made in the software for this feature. One of 16 preprogrammed positive/negative SSLO supply voltage pairs is selected via a single digit switch. All automatic mode operations may be manually executed using interface panel controls.

D. Software Subsystem

The real power as well as a substantial fraction of the overall cost of a computer-controlled test system is directly related to software. The software dictates system accuracy, operation requirements, and flexibility. The software is, indeed, the key subsystem of the test set.

The SSLO T/S features a supervisor/worker programming environment. The supervisor is called a process automation monitor (PAM) and is largely a standard operating system supplied with the computer. The PAM is a multiprogramming system incorporating a multilevel priority scheme for program execution. Device service routines, math routines, I/O processors, and interrupt handlers reside within the monitor. Worker programs include the specific measurement and analysis tasks as well as general support tasks such as message input/output. Worker tasks are installed into the computer on a priority basis. PAM maintains a list of the worker tasks which is periodically scanned, and initiates (or continues) execution of the highest priority task which is enabled, requested, and not in a time delay or under suspension. Test system programs are coded in symbolic assembly language.

IV. TEST SYSTEM OPERATION AND OUTPUT

In order to make an automatic test system cost effective, it operation must be as device independent and multifunctional as possible. In general, an SSLO requires the following tests at three or more test temperatures (cold, room, hot).

1) Determine the voltage limits which provide tuning over a specified frequency range.
2) Obtain the tuning characteristics (voltage versus frequency) over the specified frequency range. Determine best fit, and maximum and minimum incremental slopes.
3) Measure output power as a function of frequency. Verify adherence to minimum/maximum output specifications.
4) Measure noise power over the required tuning range and verify a maximum criterion is not exceeded.
5) Check harmonic and spurious output response over the specified tuning range.

The SSLO T/S test format provides for efficient fulfillment of the preceding requirements regardless of device characteristics.

A special task called the ID TASK is utilized to specify device characteristics and to set up test system configuration accordingly. Device type, serial number, and test temperature (which appear on all output), frequency band, connection port, dc requirements, and number of tuning lines with associated interface tuning line gains are registered utilizing the ID TASK.

There are a total of ten measurement or data output tasks called FUNCTION TASKS. Execution of a FUNCTION TASK is requested by task name, a five letter acronym which suggests task function. Execution of any task simply requires appropriate operator response to standard requests generated automatically by the operating system. The requests require response of ten or fewer characters specifying, for example, the device name (ID TASK) or start, stop, and increment test voltage parameters. Each operator input is checked for format and content validity by the operating system.

As an example of system power, it takes less than 5 s after inputting five test parameters to: 1) collect 100 voltage/frequency data points; 2) calculate the least squares best-fit characteristics; 3) provide a CRT presentation including a plot of the tuning data, a plot of the deviation of test data from the calculated best-fit curve and values of best-fit slope and maximum and minimum incremental slopes.

Measurement and data display repeat cycles of tuning or power characteristics at current test parameters (sweep voltages) can be initiated at the press of a button. This is particularly useful for online device tuning.

Fig. 4 shows a computer-generated CRT display of the tuning characteristics of a Ku-band SSLO. Note that the least squares best-fit slope and maximum and minimum incremental slopes are printed near the origin of the upper data axes. The frequencies of occurrence of the critical point slopes are flagged along the frequency axis. The lower curve is a plot of the deviation of actual frequency data from the best-fit frequency.

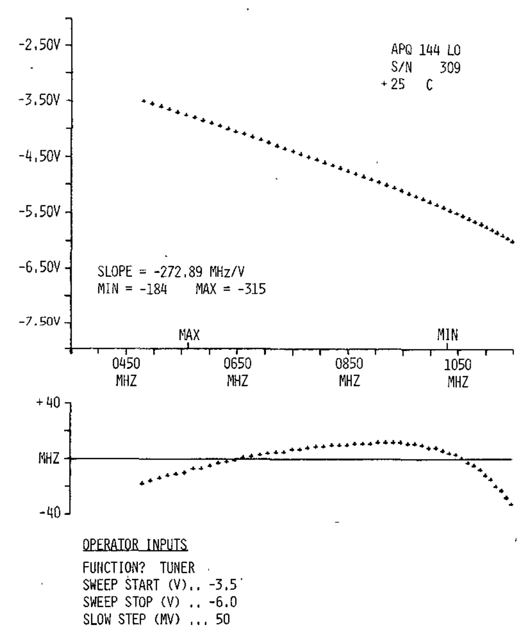

Fig. 4. Computer generated CRT presentation of the results of tuning measurements for a Ku-band SSLO.

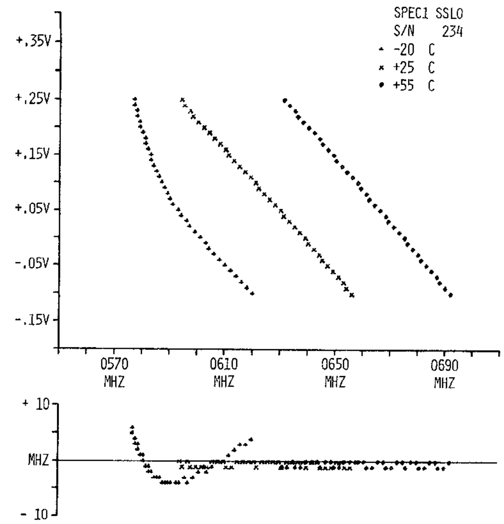

Fig. 5. Computer generated plot showing temperature effects on the tuning characteristics of an SSLO.

Fig. 5 is a computer generated plot of the tuning characteristics of a *Ku*-band SSLO as a function of temperature. Up to seven curves may be overlaid on a single set of axes. This feature is useful for sensitivity studies on a single LO or for device-to-device characteristic tracking.

V. CONCLUSIONS

Savings of 30:1 and more in test time have been realized utilizing the Automatic SSLO *T/S* instead of previously used techniques. Other benefits include: 1) standardization of test equipment and techniques; 2) standardization and simplification of test procedures; 3) improved test data format; 4) more data points/more thorough testing.

The machine is not without limitations, however. Indeed, experience has indicated it likely that only after a period of actual use in the mode for which an automatic measurement system was intended will all design requirements be recognized. Even then the machine is of a dynamic character subject to change. This principle of "automatic limitation" is especially applicable to automatic microwave measurement systems.

One way to combat "automatic limitation" is to make the system as flexible and modular as possible. Of course, there are cost tradeoff considerations which must be dealt with in these areas. For the SSLO *T/S*, two common "automatic limitations" were anticipated. First, recognizing the probability of need for software refinements, all programs were blocked to the extent possible into independent discrete tasks. These may be individually updated to any extent desired without major rework of the software system. In addition, the PAM is inherently modular in nature and is particularly efficient with regard to changing peripheral equipment configuration. Secondly, test volume forecasts indicated that requirements would exceed capability of a single machine within a relatively short period of time. In anticipation of this factor, the system software was written to accommodate from one to four nearly identical SSLO test stations—all utilizing the existing software and single computer on a time-share basis. The time-share priority execution characteristics of the system would allow different types of test stations to share the single computer. However, this would require greater software variety and increased computer storage capacity.

The most immediate general limitation of the test system is associated with data output. Currently, hard-copy print speed is 30 characters/s for tabular data and plot output averages 10 min. Although other tasks may be executed simultaneously with PLOT tasks with no detectable decrease in task time, the plotter speed limits overall throughput. An economical high-speed printer/plotter which can be shared with other test systems will be added in the near future.

Tables I and II summarize the functional capabilities and the major components of the Automatic SSLO *T/S*, respectively. This system is but one example of a cost-effective application of custom test automation. Any number of today's microwave measurement problems including noise figure measurements, RF amplitude and phase at large signal and pulsed conditions, and surface wave device characterization could be similarly automated. It is by no means unrealistic at this point to envision the concept of an integrated centralized microwave test facility. Such a facility consisting of several general-purpose modular automatic systems could conceivably accommodate 75 percent or more of all microwave testing for a full-scale microwave systems manufacturer.

TABLE I
FUNCTIONAL CAPABILITIES OF THE AUTOMATIC SSLO TEST SYSTEM

Automatic Measurements	• VCO voltage versus frequency tuning characteristics. • Determine voltages required to tune to specific frequencies. • Signal power versus frequency/tuning voltage. • 60 MHz side-band noise power.
Other Measurements	• Spectrum analysis with optional computer-controlled sweep of the device under test.
Analysis Capability	• On-line least-squares linear curve fit • Determination of deviation of actual data from best fit characteristics.
Output	• CRT display of tuning, power and analysis data • Hard copy plots and overlay plots • Tabularized data

TABLE II
LIST OF MAJOR COMPONENTS OF THE AUTOMATIC SSLO TEST SYSTEM

Controller Processor	Texas Instruments Model 960A Minicomputer W/24K MOS memory
Peripheral Equipment	Texas Instruments Model KSR 733 Thermal Teleprinter Data Products Model 300 Card Reader EAI Model 140 Dataplotter Tektronix Model 611 Storage CRT
Measurement Instrumentation	HP Model 8555A Spectrum Analyzer System W/ Preselector Pacific Measurements Model 1036 Power Meter HP Model 5340A Frequency Counter
Miscellaneous Equipment	Statham Model 60-5 Temperature Chambers Tustin Model 1535 D/A Converter Texas Instruments SSLO Test System Microwave Multiplexer Texas Instruments SSLO Test System Controller

REFERENCES

[1] R. A. Hackborn, "An automatic network analyzer system," *Microwave J.*, vol. II, pp. 45–52, May 1968.
[2] S. F. Adam, "A new precision automatic microwave measurement system," *IEEE Trans. Instrum. Meas.* (*1968 Conference on Precision Electromagnetic Measurements*), vol. IM-17, pp. 308–313, Dec. 1968.
[3] M. Cunningham, "Automation speeds spectrum analysis," *Microwaves*, pp. 48–52, June 1973.
[4] J. R. Humphrey and C. H. Dale, "Innovations are key to fully automated testing," *Microwaves*, pp. 54–58, June 1973.
[5] M. I. Skolnik, *Introduction to Radar Systems.* New York: McGraw-Hill, 1968, p. 386.