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"DO-IT-YOURSELF" LOCK-IN AMPLIFIERS – RADIO AND AUDIO FREQUENCIES*

K. W. LAMERS

Lawrence Radiation Laboratory, University of California, Berkeley, California, U.S.A.

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We describe two specific lock-in amplifiers, one designed for radio frequencies (rf), and the other for audio frequencies (af). Both have been built and tested by chemists with limited electronics backgrounds.

The af unit, which uses commercial circuit modules, was designed for an electron-spin-resonance spectrometer locking a klystron's frequency to that of a resonant cavity. The lock-in amplifier has been adapted to nuclear-magnetic-resonance work by combining it with a marginal oscillator. The frequency range is 40 to 20000 Hz, but this is easily extended.

The rf unit, designed for measuring differential pressures on the order of 0.1 μ with an accuracy of several percent, can detect capacitance changes on the order of 10^{-18} F. Although designed for 2.7 MHz, it can be adapted to other radio frequencies. The rf unit uses Nuvistor tubes to minimize the instability problems normally encountered at radio frequencies.

1. Introduction

High-performance lock-in amplifiers are commercially available, but in many cases the price is prohibitive for experimenters with limited funds. Furthermore, some of these units incorporate features unnecessary to a given application, and the additional complexity is undesirable. Also, commercial lock-in amplifiers do not yet encompass the entire radio-frequency spectrum. In some cases one has no alternative but to design his own. The lock-in amplifiers described here are relatively easy to build and test. Proper testing requires an oscilloscope and a signal generator, but our chemists have had little trouble in adapting to these instruments. Additional information in the form of photographs, templates, construction details, and test procedures is available[1]).

The af unit is designed around commercial circuit modules so that much of its circuitry need not be fabricated. Performance compares favorably with specifications published for some commercial units, but ours is less flexible in selecting frequency. It is best used in applications where frequency changes are seldom made, but it can be adapted to variable-frequency operation. Fixed-frequency operation is quite suitable for many applications, however, and reduces complexity of the instrument.

The rf lock-in amplifier does not employ circuit modules, but uses Nuvistor tubes instead. Nuvistors, which are much smaller than conventional tubes, offer advantages at radio frequencies, as discussed later.

2. General considerations

Lock-in amplifiers are discussed elsewhere[2]), so this discussion is somewhat limited. Basically, a lock-in amplifier does much the same thing as a tuned amplifier but does it better. The principal difference is that lock-in amplifiers are phase-sensitive. Also, they can operate at bandwidths very much narrower than are possible with a conventional tuned amplifier operating at the same frequency. The reasons that lock-in amplifiers can operate at such narrow bandwidths are:

a. the information (signal) sought is amplitude-modulated by a reference, usually of audio frequency or higher;

b. the reference also gates a synchronous detector that responds to the gating frequency only;

c. if the reference frequency changes, the gating changes correspondingly, so that the lock-in always remains "in tune".

Lock-in techniques are commonly used to recover signals 40 dB below the ambient noise level. These techniques are very effective because:

a. they minimize noise generated by the amplifying devices used[3]);

b. they reduce white noise associated with the signal inversely as the square root of bandwidth (the degree to which bandwidth can be reduced is related to the highest frequency of the information sought);

c. they discriminate against noise at the "tuned" frequency, but of random phase.

Lock-in techniques minimize noise generated by the amplifying devices used because:

a. the signal is modulated to translate its spectra from a band centered around zero frequency to a band centered about a higher frequency (the modulation frequency[4]);

b. most amplifying devices have noise spectra that vary as the reciprocal of frequency[5]);

c. translation to a higher frequency moves the signal to a frequency where less noise is introduced by the amplifying devices used. In general, the modulating

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TABLE 1

Values for frequency-sensitive components of fig. 2.

Component	R (kΩ)	C (μF)	$C_{560\ \mathrm{Hz}}$ (μF)
Parallel-T network	3	$\sim 53/f$[a]	0.10
Oscillator network	3.6	$\sim 18/f$[b]	0.033
C_1 and C_2[c]		$\sim 4/f$	0.0068
C_3 and C_4[d]		$\sim 5.6/f$	0.01

[a] From ref. [8]), ch. 16, p. 24.
[b] From ref. [8]), ch. 6, p. 40.
[c] Reactance ≈ 40 kΩ at operating frequency.
[d] Dependent upon ripple tolerable.

frequency should be greater than 100 Hz when vacuum-tube amplifiers are used and greater than 1000 Hz when transistor amplifiers a used.

3. Audio-frequency lock-in amplifier

The principal components are shown in fig. 1. The af unit (fig. 2 and table 1) uses three linear-amplifier modules. One amplifier in conjunction with a network comprises the oscillator. Another type of module includes three emitter-followers in one package. Most frequency-determining elements (a parallel-T network for the first amplifier stage and a network for the oscillator) are fabricated into blank containers supplied by the module manufacturer. A preamplifier which uses two linear-amplifier modules has been described elsewhere[1]).

The frequency range, determined by the transformers used, is approximately 40 to 20000 Hz. This range can be extended if the transformers are omitted[2]). The gain (dc out/rms in) is about 3000. The equivalent input noise measured 1 μV rms at 560 Hz with the input terminals shorted and a 2-sec time constant. Linearity checked better than $\pm 1\%$ of full scale with dc outputs up to ± 2V.

4. Radio-frequency lock-in amplifier

The rf unit was designed for measuring differential pressures on the order of 0.1 μ with an accuracy of several percent. When the unit was designed, commercial micromanometers of sufficient sensitivity were not available, and so we designed our own. For reasons described elsewhere[6,7]), we elected to sense pressure difference with a membrane manometer, constructed like a differential capacitor. The capacitor forms two legs of a resonant-bridge network excited by a 2.7-MHz source (fig. 3). Bridge output is amplified and detected with the lock-in detector unit shown in fig. 4. The frequency of 2.7 MHz was chosen for several reasons[6]), some theoretical and some practical.

The rf unit was not designed around circuit modules because

a. most modules with adequate frequency response are subject to oscillation, so we might not have been able to realize as much gain;

b. the signal amplifier should be tuned, so there is no particular advantage to wide-band devices – the gain-bandwidth product is wasted;

c. high-frequency modules were more expensive; if modules were used, the rf unit would have cost about three times as much as it did with Nuvistors;

d. Nuvistors operate at higher voltages, so the output levels are higher and the need for a dc amplifier is eliminated in some cases.

Nuvistor tubes, which minimize duplication problems, are used in the rf unit because:

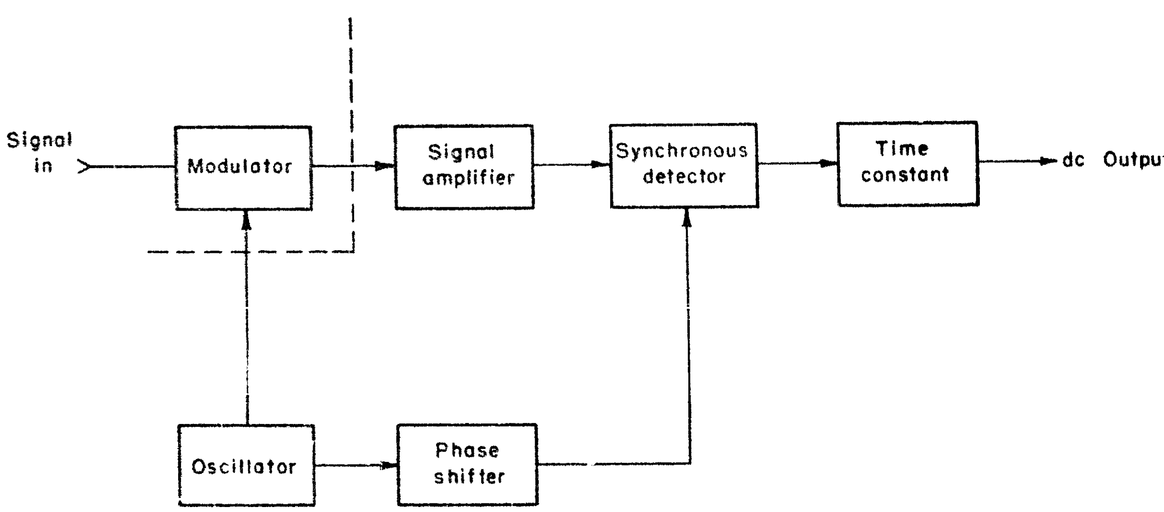

Fig. 1. Block diagram of the af unit. The modulator, which is external to the af unit, can take many forms, electrical or mechanical.

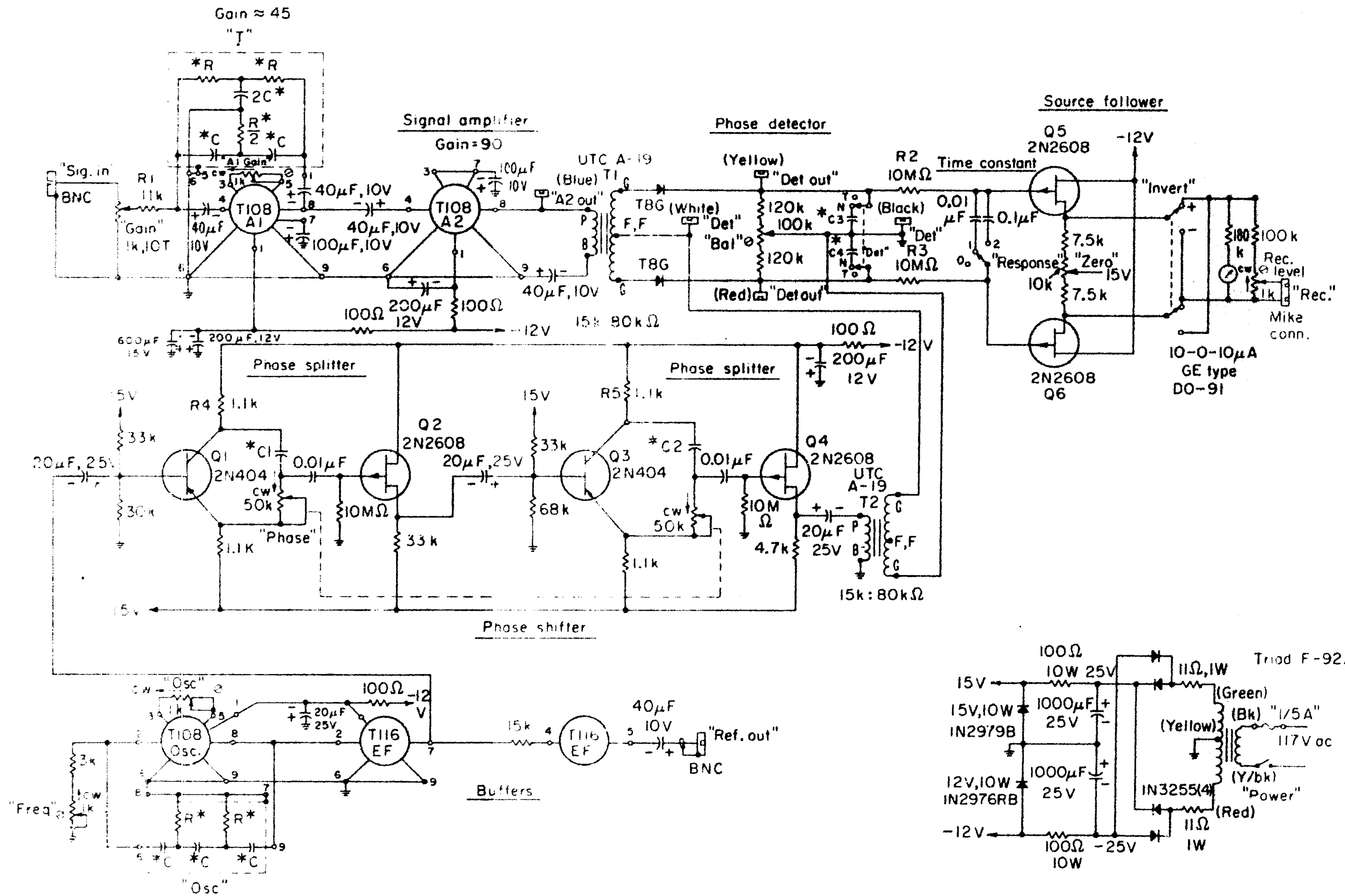

Fig. 2. Schematic diagram of the af unit. Modules T-108 and T-116 are manufactured by Engineered Electronics Company. All resistors are ¼ W, 5% carbon, unless indicated otherwise. Phase control is a 2-gang, 2 W, Ohmite CCU-5031. All capacitors not polarized are Mylar. BNC connectors are insulated from ground, DAGE 4890-1. Components indicated by * are frequency sensitive; their values can be deduced from table I. When operating at 12 kHz, the capacity unbalance of T1 caused detector unbalance and zero shift with phase. This was corrected by substituting a UTC type A-22 for T1.

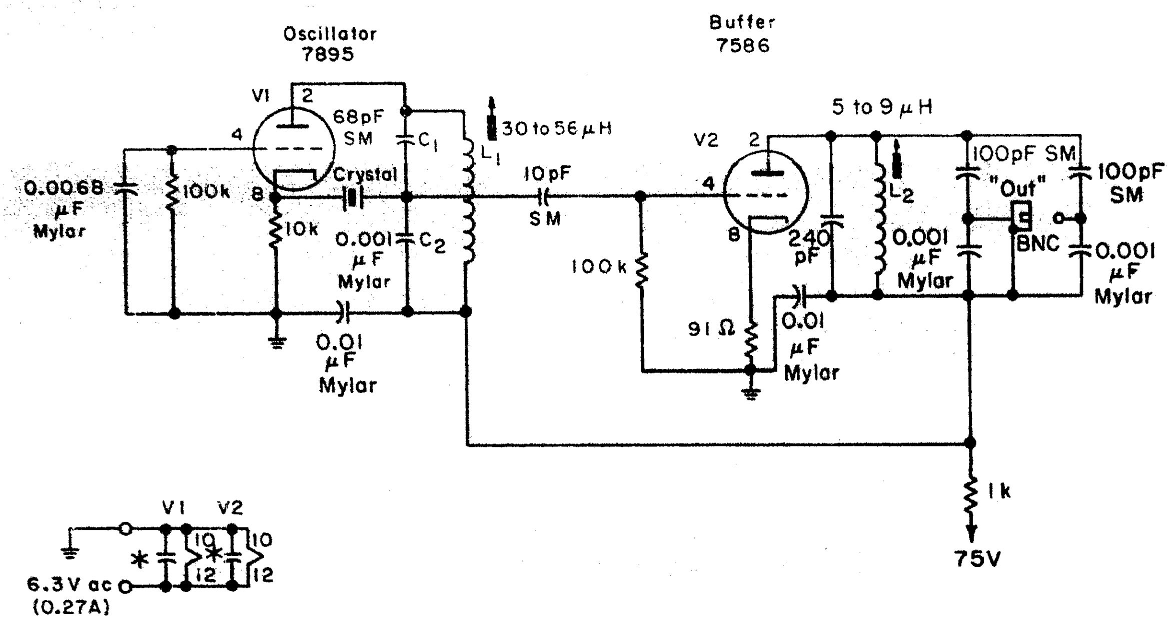

Fig. 3. Schematic diagram of the rf lock-in generator unit. All resistors are ¼ W. Inductance L_1 comprises 64 turns of no. 32 Formvar wound on National Radio Corp. form XR50; L_2 is 25 turns of no. 22 Formvar wound on form XR50. The crystal (type CR-18/U) operates at 2762.500 kHz. Capacitors marked with an asterisk are 1000-pF, ceramic feed-through type; those designated SM are silver-mica. ***Note added in proof*: BNC "Out" connector should tie to ground, not to lower side of L_2.**

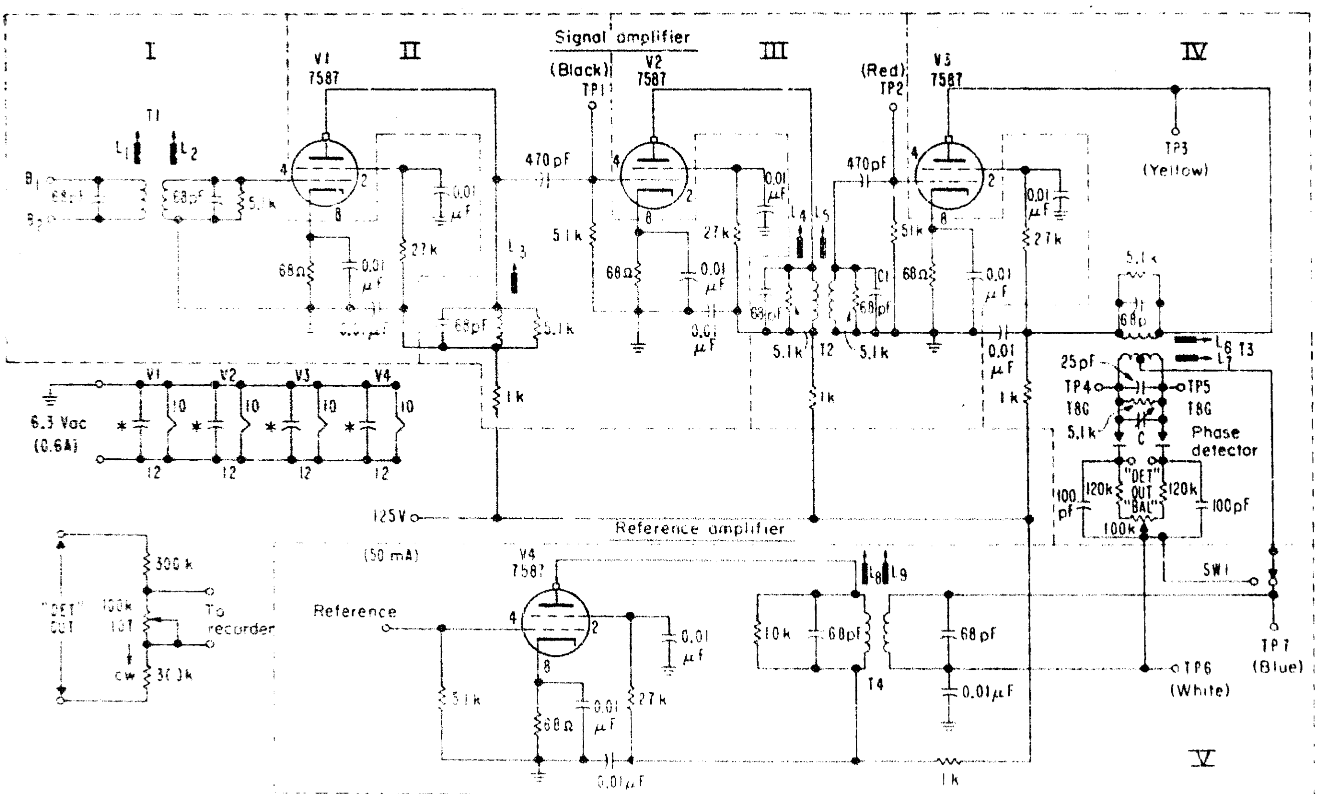

Fig. 4. Schematic diagram of the rf lock-in detector unit. The 27-kΩ resistors are ½ W; all others are ¼ W. Asterisks denote 1000-pF ceramic feed-through capacitors; all other picofarad capacitors are silver-mica, and all μF capacitors are Mylar. C is a 7- to 45-pF ceramic trimmer. All inductors comprise 64 turns of no. 32 Formvar wound on National Radio Corp. form XR50; L_7 is center-tapped. Transformers T1 through T4 comprise the relevant inductors, mounted ⅜" between centers. The primary of T1 should be connected series-resonant if the source resistance is less than the inductive reactance of L_1 (700 Ω at 2.7 MHz). The roman numerals indicate the compartments in which the components are mounted. A low-impedance potentiometric recorder can be driven by a divider across the DET OUT terminals, as shown. The power supply is not shown.

a. the unit was to be duplicated and operated by those with little or no electronic background (transistors were not used because of their "loose" tolerances; good design can compensate for this, but engineering funds were limited);

b. Nuvistors are very small and generate little heat, which permits us to confine them to well-shielded compartments, thus minimizing instability problems;

c. their combination of high transconductance with low interelectrode capacitance permits considerable gain without neutralization[8]).

Performance, as related to the original application is described in[7]). The important specifications for the *modified* unit are

a. gain (dc out/rms in) is approximately 2700, depending upon source resistance;

b. signal-channel bandwidth is 220 kHz;

c. linearity is approximately 1% of full scale at outputs up to ± 2.4 V. [Input noise was not measured, but we were able to detect capacitance changes on the order of 10^{-18} F using the unit of [7])].

5. Applications

The af unit was designed for an electron-spin-resonance spectrometer now being developed at this laboratory. Two lock-in amplifiers are used, one for automatic frequency control (12 kHz), another for the signal channel (560 Hz). We have adapted the af unit to nuclear-magnetic-resonance work, using it with a marginal oscillator to detect the nuclear resonant frequency of a sample exposed to a magnetic field. This frequency, directly proportional to field strength, can be measured with precision and affords an accurate measurement of field intensity. Another application involves automatic frequency tracking when the magnetic field is varied.

The rf unit was designed for measuring very small atomic concentrations. These concentrations are converted to pressure differentials, then sensed with a membrane manometer, as discussed earlier. In achieving the design objective, we were able to detect capacitance changes on the order of 10^{-18} F. This unusual sensitivity to dielectric properties could be useful in other areas; we are considering its application to diagnostic studies of gaseous media. Another application involves the detection of light modulated at 2.7 MHz.

The af unit was designed for an electron-spin-resonance spectrometer being developed under the direction of Professor H. S. Johnston, Inorganic Materials Research Division. The rf unit was designed for a differential micromanometer developed under the direction of Professor D. N. Hanson, Department of Chemical Engineering. The manometer was developed in collaboration with Dr. P. Rony, now affiliated with the Monsanto Chemical Company, St. Louis, Missouri.

References

1) K. W. Lamers, Lawrence Radiation Lab. Rep. UCRL-16632 (Jan., 1966).

2) R. D. Moore, Electronics **35**, no. 23 (1962) 40.

3) Lock-in amplifiers are commonly driven by other devices that generate noise, a receiver for example. The lock-in technique minimizes noise generated by devices preceding it, provided that those noises are not modulated by the reference.

4) H. S. Black, *Modulation Theory* (D. Van Nostrand, New York, 1953) p. 39.

5) R. D. Moore and O. C. Chaykowsky, Princeton Applied Res. Techn. Bull. **109** (1963).

6) K. W. Lamers, Lawrence Radiation Lab. Rep. UCRL-11218, Part I (Oct., 1964).

7) P. R. Rony, Lawrence Radiation Lab. Rep. UCRL-11218, Part II (April, 1965).

8) R. Landee, D. Davis and A. Albrecht, *Electronic Designer's Handbook* (McGraw-Hill, New York, 1957) p. 7.