Simple design for a frequency-independent voltage-controlled phase shifter

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A very simple general-purpose phase shifter is described here, that can be linearly voltage controlled in a wide frequency range. This device allows us to implement the standard lock-in amplifier into a vector tracking lock-in amplifier.

The phase-locked-loop (PLL) technique exploited by the *vector tracking* lock-in amplifiers[1] has proven useful in achieving very accurate resonant frequency measurements in a vibrating-fiber microbalance for adsorption isotherm studies.[2]

The block diagram of a vector tracking lock-in amplifier is shown in Fig. 1: here the dc output signal $V_{\rm out}$ is proportional to the amplitude of the input signal $V_s = V_{so} \cos(\omega_1 t)$, even in presence of a large uncorrelated signal noise $n(\omega t)$, and it does not depend on the phase angle φ between V_s and the reference synchronous signal $V_R = V_{RO} \cos(\omega_1 t + \varphi)$.

The output $V_{RO} \cos(\omega_1 t + \varphi + \Phi)$ of a voltage-controlled phase shifter (VCPS) is used to drive the reference channel of the "in-phase" demodulator, and a constant $\pi/2$ phase shift is provided to the reference channel of the quadrature demodulator.

The output V_φ of the quadrature demodulator is used as negative feedback to control the VCPS, giving $\Phi = -\varphi$ at closed loop.

In other words the phase error of the reference signal is automatically zeroed. This feature is particularly important when φ is unknown (as for signals buried in noise) or changing with time.

Demodulators (or phase-sensitive detectors) are essentially multipliers (or choppers) followed by a low-pass filter,[3] and they are also commercially available as low price modules.[4]

Voltage-controlled phase shifters, on the other hand, are usually built-in blocks in sophisticated two-phase lock-in amplifiers[5] and they are not available as separate devices.[6]

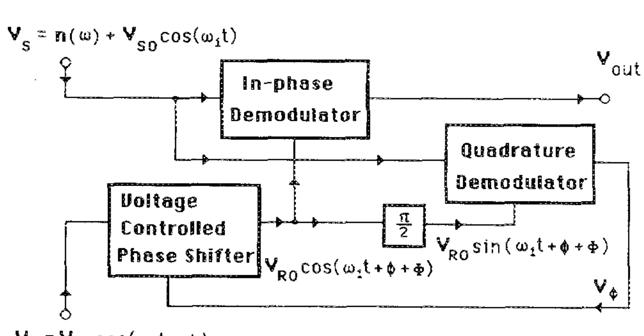

FIG. 1. Simplified block diagram of a vector tracking lock-in amplifier.

A functional block diagram of our VCPS is shown in Fig. 2, and the signal waveforms at the output of single blocks are reported in Fig. 3.

A zero cross detector provides two square waves with $\varphi = 0$ and $\varphi = \pi$ phase angle with respect to the input signal (V_A and V_B).

A frequency doubler produces the trigger signal V_T for a voltage-controlled one shot.

The pulse width ΔT of the one-shot output is controlled by the reference voltage $V_{\rm ref}$ and by the slope of the ramp signal V_c appearing across the capacitor C.

A frequency-to-current converter charges C at a constant current I which is proportional to the signal frequency f: $I = \beta f$.

When the one shot is triggered, the output V_D goes high and it stays high until V_c reaches $V_{\rm ref}$. At this point the

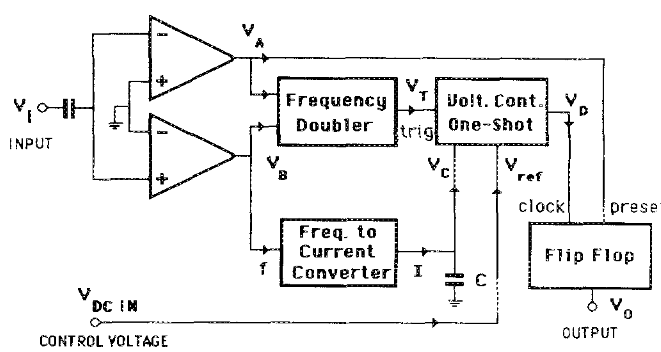

FIG. 2. Block diagram of the voltage-controlled phase shifter.

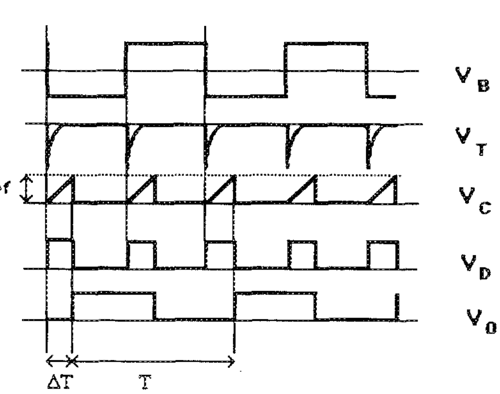

FIG. 3. Time correlation of the signal waveforms appearing at each block output.

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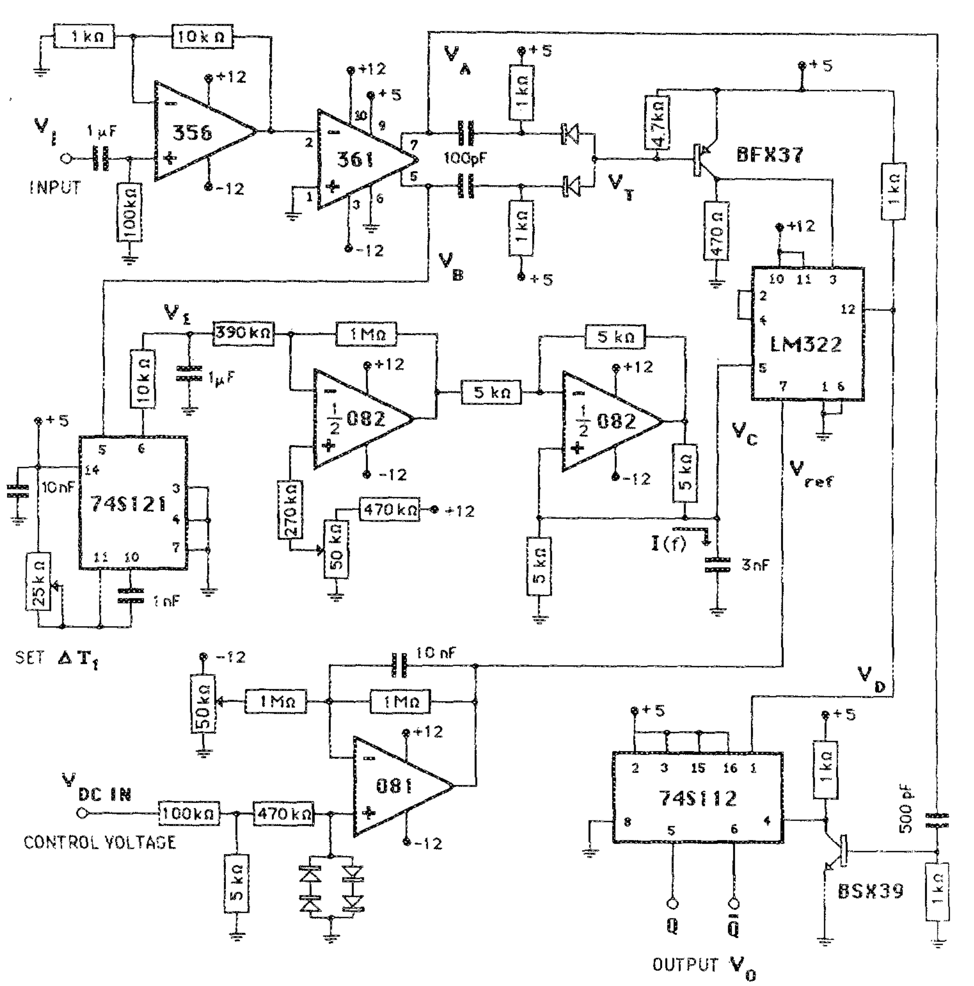

FIG. 4. Detailed circuit of the voltage-controlled phase shifter.

output goes low and the capacitor is shorted to ground until the arrival of a new trigger pulse.

The pulse width ΔT is, therefore, $\Delta T = V_{\text{ref}}\, C/I = T\, V_{\text{ref}}\, C/\beta$, where $T = (f)^{-1}$.

The negative edge of the signal V_D is used as a clock for the flip–flop output stage which provides the delayed output signal V_0.

The ratio of the delay ΔT to the period T gives the frequency-independent phase shift $\varphi = 2\pi\Delta T/T = V_{\text{ref}}\, C/\beta$.

Using the Q or the $\bar{Q}$ output of the flip–flop allows phase shifts in the ranges 0–π and π–2π, respectively. The correct phase relationship is assured by using V_A as a preset signal.

In Fig. 4 the complete circuit is shown. The input stage of the zero cross detector is an ac coupled fast amplifier (LF356).

The V_A and V_B signals are provided by a high-speed complementary TTL output voltage comparator (LM361).

The frequency doubler is simply made by adding the differentiated and rectified V_A and V_B signals.

The voltage-controlled one shot is obtained from a fast IC timer (LM322). The upper limit (f_u) of the working frequency is imposed by the minimum value of ΔT (related to the slew rate of LM322) as well as by the minimum value φ_m required for the phase shift: $f_u < \varphi_m/(2\pi\Delta T)$.

The frequency-to-current converter is built using a monostable (SN74S121) whose output signal V_1 is averaged by a low-pass filter.

The pulse duration ΔT_1 of signal V_1 must be shorter than $(f_u)^{-1}$. After the low-pass filter the voltage is, therefore, $\langle V_1 \rangle = 5\Delta T_1 f\,(\text{V})$.

An inverting amplifier ($\frac{1}{2}$TL082), with an offset correction to compensate the 74S121 pedestal, provides the negative voltage suitable for the voltage-controlled current source ($\frac{1}{2}$TL082).

The V_0 signal is directly taken from the complementary output of the JK-edge-triggered flip–flop (SN74S112).

A fixed phase shift φ_0 is manually set by selecting the value of ΔT_1 and a protected input is available for positive and negative values of the voltage control ($V_{\text{dc in}}$): $\Delta\varphi = \varphi_0 + kV_{\text{dc in}}$.

The stability of $\Delta\varphi$ vs frequency is better than 5° in the range 1 kHz $< f <$ 20 kHz, and the time stability is better than 0.1° over several hours.

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[1]M. L. Meade, *Lock-in Amplifiers: Principles and Applications* (Peter Peregrinus, London, U. K., 1983).
[2]L. Bruschi and G. Torzo (to be published).

[3]S. F. Carter and E. A. Faulkner, Electron. Lett. 3, 339 (1977); J. Dratler, Rev. Sci. Instrum. 48, 327 (1977); I. Riess, Rev. Sci. Instrum. 53, 1388 (1982); L. Bruschi, R. Storti, and G. Torzo, Rev. Sci. Instrum. 56, 427 (1985).

[4]Evans Electronics, Berkeley, CA 94705.

[5]For example: model 393 from Ithaco, Ithaca, NY 14851, or model 5209 from PAR, Princeton, NJ 08540, or model SR530 from Stanford Research System, Palo Alto, CA 94306.

[6]A VCPS, designed to work at frequencies below 1 kHz, was reported by J. E. Potzick and B. Robertson, Rev. Sci. Instrum. 52, 280 (1981).

Method to fabricate split coaxial line uhf probes for high-resolution NMR experiments

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A conventional Helmholtz coil used in a uhf high-resolution NMR probe is usually constructed from copper or silver bands instead of thin wires. This paper proposes a novel probe fabrication process by which the entire tank circuit of the probe can be etched or cut out from a piece of copper foil. A balanced structure with split coaxial line as rf feeders is illustrated.

The use of a superconducting magnet to generate a Z-axis static field for nuclear-magnetic-resonance (NMR) experiments has stimulated quite a number of new ideas with regard to probe design.[1–9] The most popular probe configuration consists of a pair of saddle-shaped Helmholtz coils having its b_1 field axis on the XY plane. Although the product of filling factor by quality factor of this kind of probe is inferior to that of a conventional N-turn solenoidal coil operating under the same conditions,[10] the Helmholtz coils nevertheless allow sample spinning along the Z axis and also produce a relatively homogeneous rf field[11] for spin excitation.

As the operating frequency increases in accordance with the available static field $\mathbf{B}_0$, the form of Helmholtz coils has evolved and finally taken the familiar shape one now encounters in most commercial high field NMR spectrometers [Fig. 1(a)]. The two rf current feeders usually extend a few centimeters from the coil so that the presence of tuning and matching components connected to them does not disturb appreciably the static field homogeneity at the sample level.

In order to reduce stray inductance of the rf feeders, the two bands are sometimes formed into a strip transmission line [Fig. 1(b)]. It can be imagined that by widening the width of the feeders or placing one over the other, or the two combined, some other forms of probes can be developed to meet this requirement. The primary aim of these structures is to transform the feeders into a capacitive element, together with the inductive part of the probe to form a LC tank circuit. The latter are either made from handcut silver or copper foils pasted onto a support,[2,8] or by direct electro-chemical deposit of copper onto a fused-quartz tube.[1,4] The following gives an account of a process of probe fabrication by which the rf tank circuit can be etched or cut out directly from a copper foil. Moreover, the upper band now forms a continuous ring and requires no solder to close the circuit.

Figure 2 (a) shows the art work or the complete set of copper foils etched out by a photoresist process for a probe of outer and inner diameter respectively equal to D and d. The upper portion (A) is identical to the lower portion (B) separated by a slit (s) of length $\pi D/2$. When this foil is folded over along line MN and with the fused-quartz support threaded through s, one can build the Helmholtz coil together with its feeders in this manner by wrapping the entire foil around the tube [Fig. 2(b)]. The width of A or B should be less than $\pi D/2$ to avoid overlapping each other for obvious reasons. To transform the feeders into part of a split coaxial line, another cooper tube made from a rectangular foil (G) of width πd is then pasted onto the inner wall of the quartz support. For clarity, this tube is shown outside the support in Fig. 2 (b). This structure is equivalent to a LC tank circuit if the length k of A, B, or G satisfies the following condition:

$$k \leqslant c/(2\pi F\sqrt{\epsilon_r})\ \arctan\ (2\pi FL/Z_0),$$

where L is the inductance of the Helmholtz coils, c is the velocity of light, F is the operating frequency of the probe, ϵ_r is the dielectric constant of the support tube, and Z_0 is the characteristic impedance of the rf feeders.

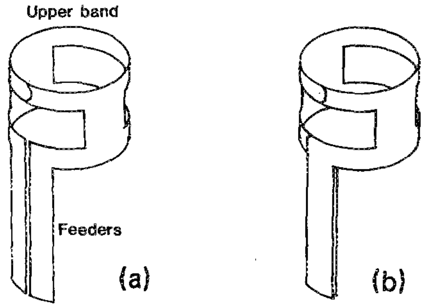

FIG. 1. Helmholtz coils for a high-frequency NMR probe. (a) with side-by-side parallel rf feeders and (b) with overlapping feeders.