Monolithic waveform generation

It is now possible to duplicate the capabilities of a complex waveform or function generator in a single monolithic chip

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Waveform or function generators find a wide variety of applications in communications and telemetry equipment, as well as for testing and calibration in the laboratory. Almost all of the waveform generators available at present use discrete (nonintegrated) circuit design techniques for waveform generation and shaping. The basic generating, modulating, and shaping methods used in most of these instruments are either directly suitable for, or adaptable to, monolithic integration.

Monolithic integrated circuits offer some inherent advantages to the circuit designer, such as the availability of a large number of active devices and close matching and thermal tracking of component values. By making efficient use of the capabilities of integrated components and the batch-processing advantages of monolithic circuits, it is now possible to design integrated waveform generator circuits that can provide a performance comparable to that of complex discrete generators, at a very small fraction of the cost. Some of these design techniques and capabilities will be described, including design and performance characteristics of a monolithic waveform generator with sinusoidal, triangular, ramp, sawtooth, and pulse output waveforms capable of amplitude, phase, and frequency modulation.

Basic monolithic waveforms

A basic waveform generator consists of three fundamental sections: (1) a controlled-oscillator section, which generates the periodic waveform; (2) wave-shaping circuitry, which determines the output waveform; and (3) a modulator section, which is used to modulate the amplitude, phase, or frequency of the output. Monolithic design techniques for each of these sections will be reviewed briefly.

The oscillator section. The oscillator portion of a waveform generator can be of either the harmonic or relaxation type. Harmonic oscillators generate nearly sinusoidal waveforms, but often require the use of inductors or large numbers of precision components and so are not readily suitable for monolithic integration. Typical

FIGURE 1. Simple oscillator circuit for generating square and linear ramp waveforms.

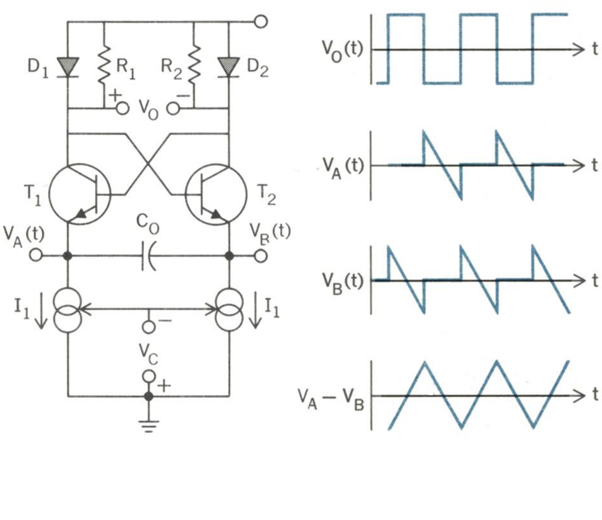
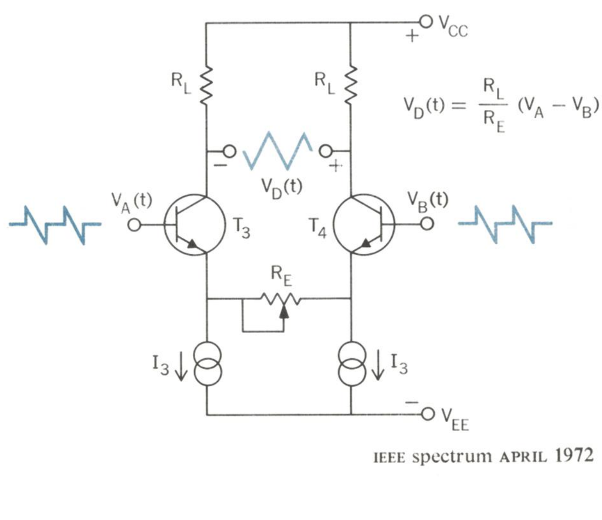


FIGURE 2. Ramp-to-triangular-wave conversion by means of a differential-gain stage.



well-known examples of these types of circuits are the Hartley, the Colpitts, the Wien-bridge, and the twin-T oscillators.

Relaxation or switching oscillators are positive-feedback circuits that operate as self-triggered flip-flops. Typical examples are multivibrators and blocking oscillators. Among these, the basic *RC*-coupled multivibrator circuit is best suited for integration since it requires a minimum number of energy-storage elements (often only one capacitor) and its operation is not critically dependent upon device parameters. A multivibrator-type oscillator can provide three general classes of waveforms: (1) exponential ramp; (2) linear ramp; (3) square wave or pulse. The first two types of waveform can be obtained by charging or discharging a timing capacitor through either a resistor (for an exponential ramp) or a current source (for a linear ramp). The square-wave or pulse output waveform can be obtained from the first two by a trigger or level-detector circuit. For wave-shaping purposes, the linear ramp and square wave are the most convenient waveforms to work with since their harmonic content is predictable and can be easily controlled.

Linear ramp generators require the use of accurate constant-current stages. Since accurate and well-matched current sources can easily be fabricated in monolithic form, linear ramp generators are well suited to integration. These oscillator circuits have a generalized frequency expression of the form:

$$f_0 = \frac{KI_1}{C_0}$$

where K is a constant of proportionality in volts $^{-1}$, C_0 is the timing capacitance in farads, and I_1 is the charging current in amperes. In an oscillator of this type the frequency range is selected by the choice of C_0, and the frequency control can be achieved by varying the current I_1. Figure 1 is a simplified diagram of a relaxation oscillator circuit demonstrating this principle.[1] The circuit is derived from the emitter-coupled multivibrator configuration and can generate a square-wave, as well as a linear ramp, output. Its operation can be briefly explained as follows: At any given time either T_1 and D_1 or T_2 and D_2 are conducting, such that the capacitor C_0 is alternately charged and discharged by constant current I_1. The output across D_1 and D_2 corresponds to a symmetrical square wave, with a peak-to-peak amplitude of $2V_{BE}$, where V_{BE} is the transistor base–emitter voltage drop. The output V_A is constant when T_1 is on, and becomes a linear ramp with a slope equal to $(-I_1/C_0)$ when T_1 is off. The output $V_B(t)$ is the same as $V_A(t)$, except for a half-cycle delay. Both of these linear ramp waveforms have peak-to-peak amplitudes of $2V_{BE}$. The frequency of oscillation, f_0, can be expressed as

$$f_0 = \frac{I_1}{4V_{BE}C_0}$$

and can be controlled by varying the charging current I_1 by means of a control voltage V_C.

The ramp output voltages $V_A(t)$ and $V_B(t)$ can be subtracted from each other, to give a linear triangular waveform. This can be done by using a simple differential amplifier stage as shown in Fig. 2, where the output voltage $V_D(t)$ is a triangular waveform. The symmetry of the triangular and square-wave outputs can be offset by replacing one of the current sources in Fig. 1 by a current source I_2, where $I_2 \neq I_1$. Thus, the duty cycle of the output waveforms can be expressed as

$$\text{Duty cycle} = \left(\frac{50I_1}{I_2}\right) \text{ percent}$$

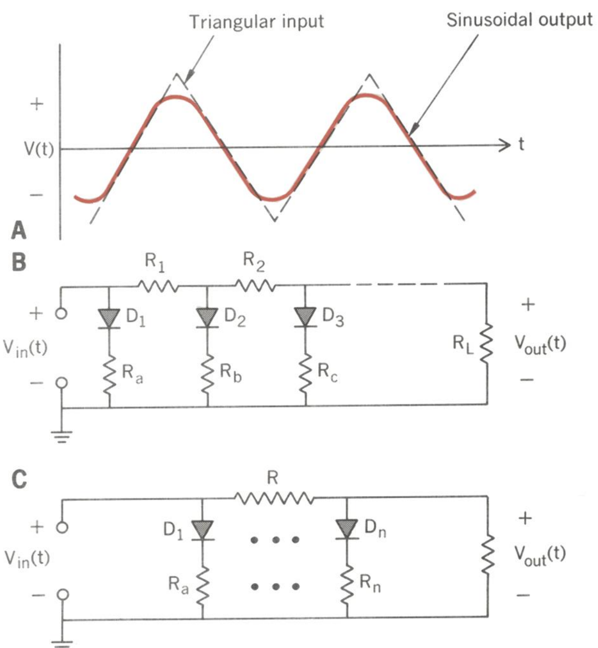
In this manner, the triangular and square-wave outputs can be converted to sawtooth or pulse waveforms.

Wave-shaping networks. After the generation of basic waveforms such as the triangle and the square wave, the next step is to convert one of these into a low-distortion sine wave. For this application, a triangular waveform is preferred over a square wave since its harmonic content is significantly lower. This initial harmonic content is further minimized by using a symmetrical triangular waveform that has a negligible even-harmonic content. This waveform can be converted into a sine wave by rounding off its peaks with the aid of a diode–resistor network as shown in Fig. 3, which also shows two practical diode–resistor circuits that can be used for this application. The distributed diode–resistor circuit of Fig. 3C can be integrated by making use of the distributed nature of the p-n junctions along a diffused resistor structure.

The wave-shaping networks of Fig. 3 can convert a symmetrical triangular-wave input into a sinusoidal output with less than 0.5 percent harmonic distortion if eight or more diodes are used. However, these wave-shaping circuits also have the disadvantage that the input-signal level, diode characteristics, and resistor ratios need to be very accurately controlled. If a higher harmonic content (of the order of 2 to 3 percent) is acceptable, the wave-shaping circuitry can be greatly simplified, and the triangle-to-sine conversion can be achieved with only two diode–resistor combinations.

As an alternate approach, the gradual cutoff of an

FIGURE 3. Conversion of a symmetrical triangular waveform into a sinusoid by the use of a diode–resistor clipping network. ·A—Input and output waveforms. B—Lumped diode–resistor chain. C—Distributed diode–resistor chain. (Sections shown for positive half-cycle clipping.)



overdriven transistor stage can also be used for wave-shaping purposes. For example, in the differential gain stage of Fig. 2, if the differential input signal drive level $(V_A - V_B)$ is increased or if R_E is decreased, an overdrive condition can exist wherein the input transistors T_3 and T_4 are driven into cutoff. Under this condition, the voltage transfer characteristic of the circuit will appear as in Fig. 4. The gradual transition between the active region and cutoff is exponential in nature and can be used to round off the sharp peaks of the input signal. In the case of the circuit shown in Fig. 2, where the input drive level is constant, this gradual cutoff can be brought about by reducing the value of the emitter feedback resistor R_E. In this manner, the triangular output of the differential stage in Fig. 2 can be converted to a sine wave with a

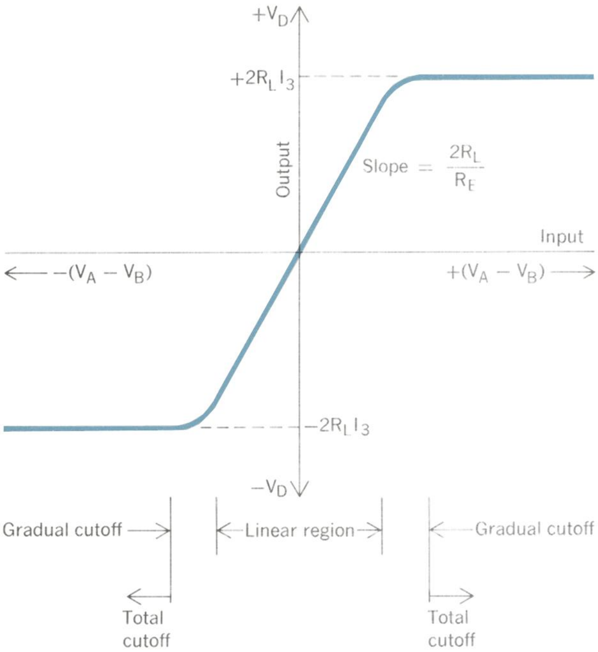
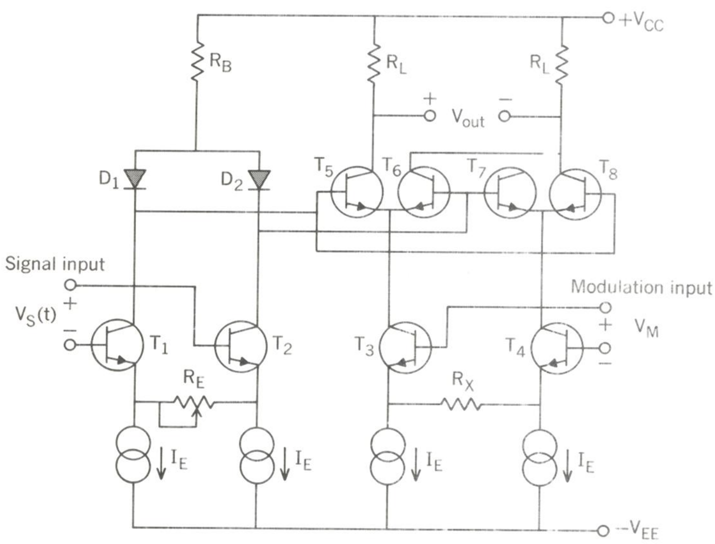


FIGURE 4. Voltage-transfer characteristic for the differential amplifier of Fig. 2 for large-signal operation.

FIGURE 5. Balanced modulator/multiplier circuit suitable for monolithic integration.



total harmonic distortion (THD) of 2.5 percent or less. This particular wave-shaping technique is used in the circuit design example described later in this article.

Modulator circuits. For waveform generator applications, balanced modulators are preferred over conventional mixer-type modulators.[2] The reason is that the balanced modulator circuits can offer a high degree of carrier suppression and thus can be used for suppressed carrier modulation as well as for conventional double-sideband AM generation. A number of balanced modulator configurations for monolithic circuit applications have been described in the literature.[3,4] The simplified circuit diagram is shown in Fig. 5. In addition to amplitude modulation, this circuit also functions as a linear four-quadrant multiplier. The output voltage $V_{out}(t)$ is a linear product of the signal input $V_S(t)$ and the modulation input $V_M(t)$:

$$V_{out}(t) = \frac{R_L}{R_E R_X I_E} V_S(t) V_M(t)$$

Typical normalized gain and phase characteristics of the balanced modulator circuit are shown in Fig. 6, as a function of the bias voltage V_M applied across the modu-

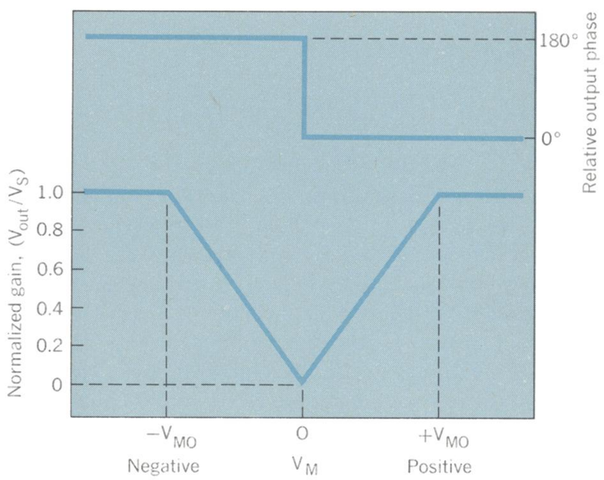
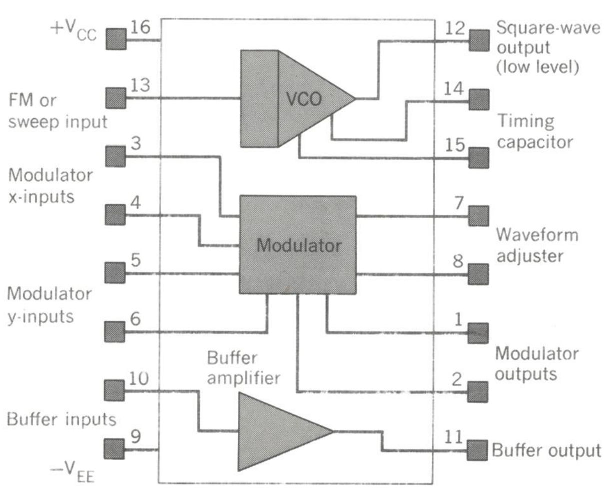


FIGURE 6. Balanced modulator/multiplier phase and amplitude transfer characteristics.

FIGURE 7. Functional block diagram of XR-205 monolithic waveform generator.



Typical applications for a monolithic waveform generator

- Waveform generation
  - Sinusoidal Sawtooth
  - Triangular Ramp
  - Square Pulse
- AM generation
  - Double sideband
  - Suppressed carrier
- Sweep generation
- Tone-burst generation
- Simultaneous AM/FM
- FSK and PSK signal generation
- On/off-keyed oscillation

lation input terminals. The output amplitude is zero for $V_M = 0$ and increases linearly with V_M for $0 < V_M < V_{MO}$ or $-V_{MO} < V_M < 0$. For modulation inputs greater than V_{MO}, either T_3 or T_4 of Fig. 5 is cut off, and the relative output amplitude remains unaffected by V_M. For $-V_{MO} < V_M < V_{MO}$, the slope of the transfer characteristic is inversely proportional to R_X. Note that the output phase is inverted when the polarity of V_M is reversed. This property of the circuit can be used for phase-shift keyed (PSK) modulation.

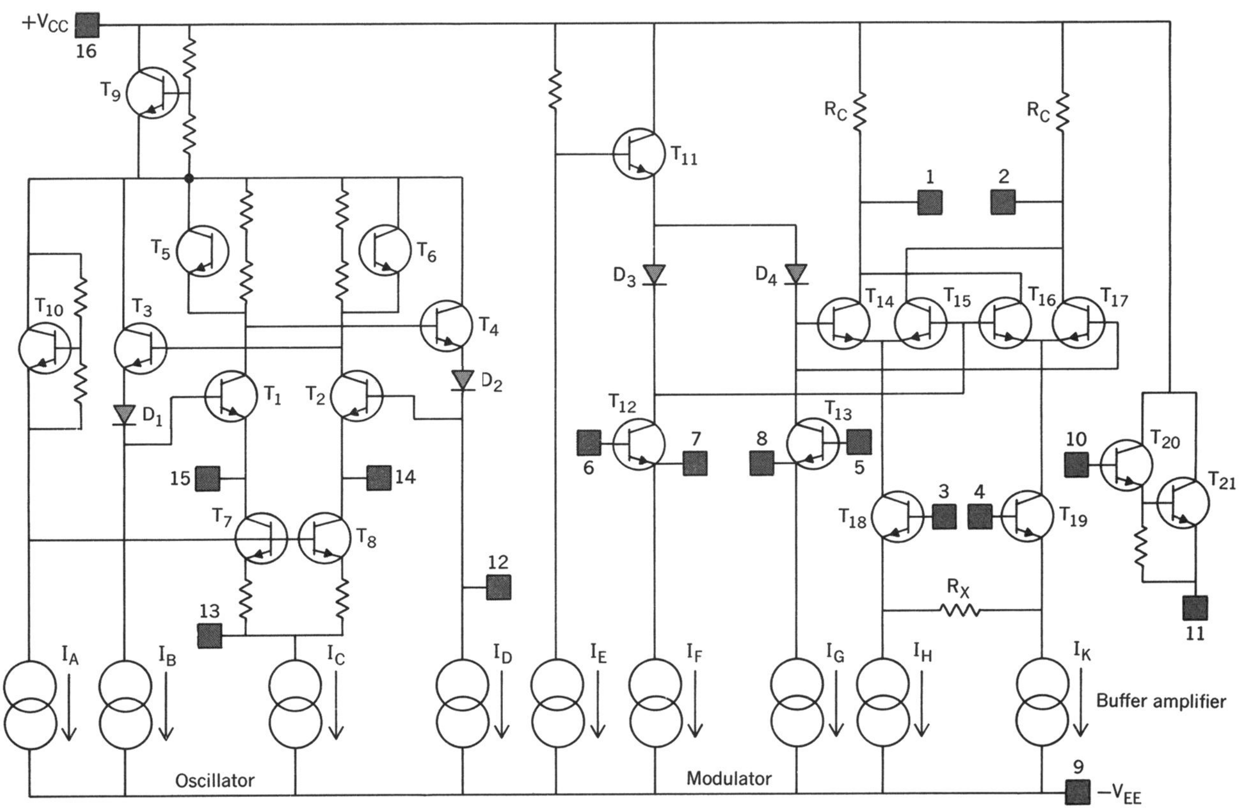
The balanced multiplier/modulator circuit of Fig. 5 also has a unique advantage for wave-shaping applications. The signal input stage formed by T_1 and T_2 can function as the differential gain stage of Fig. 2, to convert two out-of-phase ramp input signals into a symmetrical triangular wave. This wave can then be converted into a low-distortion sine wave using the "gradual cutoff" of T_1 and T_2, as described in the section on wave-shaping networks, by adjusting the emitter degeneration resistor R_E. Thus, by means of a balanced modulator circuit of the type shown in Fig. 5, wave-shaping and modulation functions can be combined in a single circuit block.

Circuit design

Each of the three basic blocks can be designed in integrated form. An entire waveform generator system, therefore, is itself well suited to monolithic integration. Figure 7 is a functional block diagram of such a monolithic generator, in terms of the circuit terminals available in a 16-pin standard IC package. For added versatility, this waveform generator system, designated XR-205, also contains a buffer amplifier that, though uncommitted to the rest of the circuit, can be connected to any one of the outputs to boost the output current drive capability. The monolithic waveform generator is designed to be suitable for one, or a combination of several, of the applications listed in the box on this page.

A simplified schematic circuit diagram of the entire monolithic generator system is shown in Fig. 8. The functional blocks and the external terminals of the circuit are also identified. The oscillator section, shown on the left side of the diagram, was designed as an emitter-coupled multivibrator, using the basic circuit configuration of Fig. 1. The frequency is set by an external timing capacitor connected across the emitters of T_1 and T_2 (terminals 14 and 15). Transistors T_1 and T_2 form the

FIGURE 8. Simplified circuit diagram of XR-205 monolithic waveform generator.



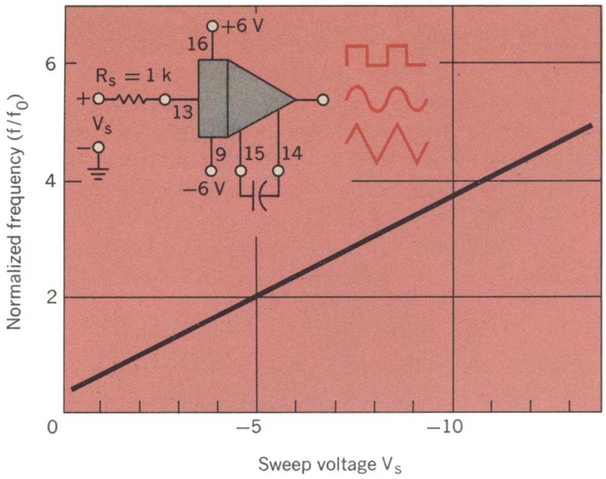


FIGURE 9. Waveform generator sweep characteristics.

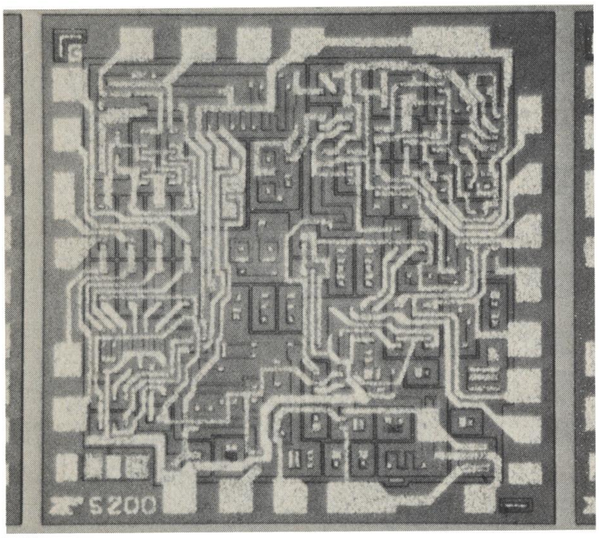


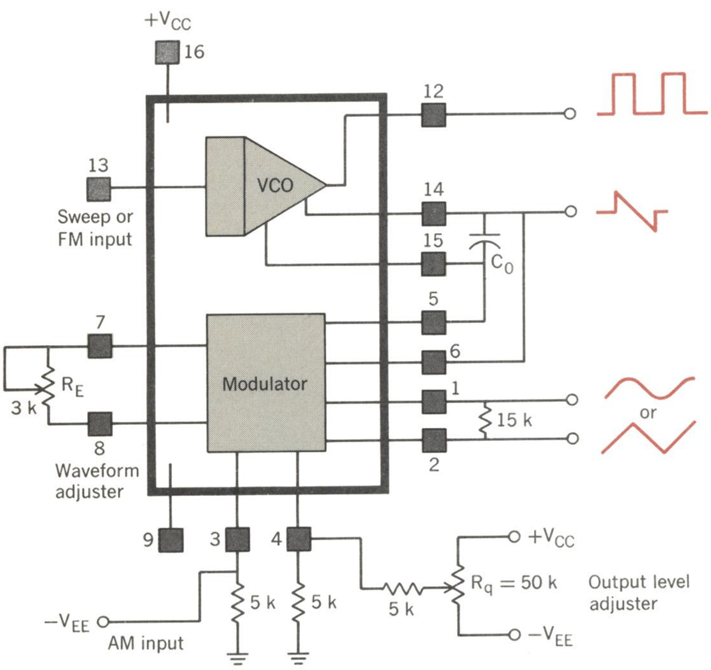
FIGURE 10. Photomicrograph of monolithic circuit chip.

gain stage for the oscillator and are interconnected to emitter followers T_3 and T_4. Transistors T_7 and T_8 serve as the current sources shown in Fig. 1, and divide the total current I_C equally between them. The oscillator frequency can be voltage-controlled by applying a dc bias to terminal 13 (see Fig. 9).

The modulator section was designed using the basic multiplier/modulator configuration of Fig. 5. With reference to Fig. 8, the internally generated ramp waveforms from the emitters of T_1 and T_2 can be directly applied to the bases of T_{12} and T_{13} and can be converted to a symmetrical triangular or sinusoidal waveform by the choice of the external resistor (R_E in Fig. 5) connected across the emitters of these transistors. The modulation input (V_M in Fig. 5) is applied to the bases of T_{18} and T_{19}, which are designated as x-inputs in the block diagram of Fig. 7. The output of the modulator section is obtained from the collectors of the cross-coupled transistors T_{14} through T_{16} (terminals 1 and 2).

The buffer amplifier section is comprised of the Darlington-connected transistors T_{20} and T_{21}. In normal operation of the circuit, the input (pin 10) of this buffer amplifier can be connected to terminals 1, 2, 12, or 14,

FIGURE 11. Generalized circuit connection diagram for monolithic waveform generator.



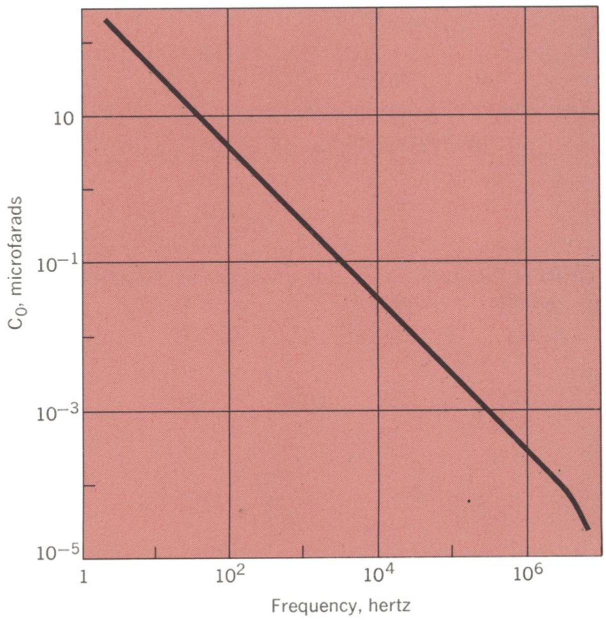
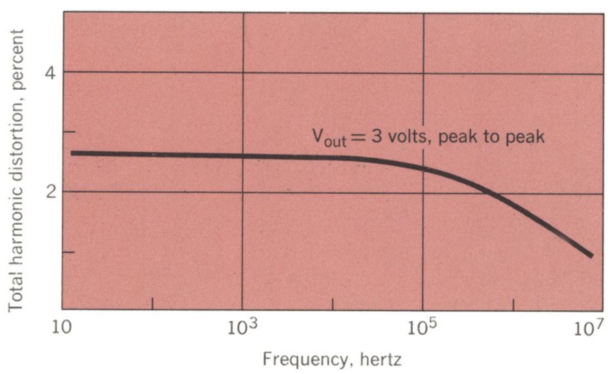


FIGURE 12. Timing capacitance vs. oscillator frequency.

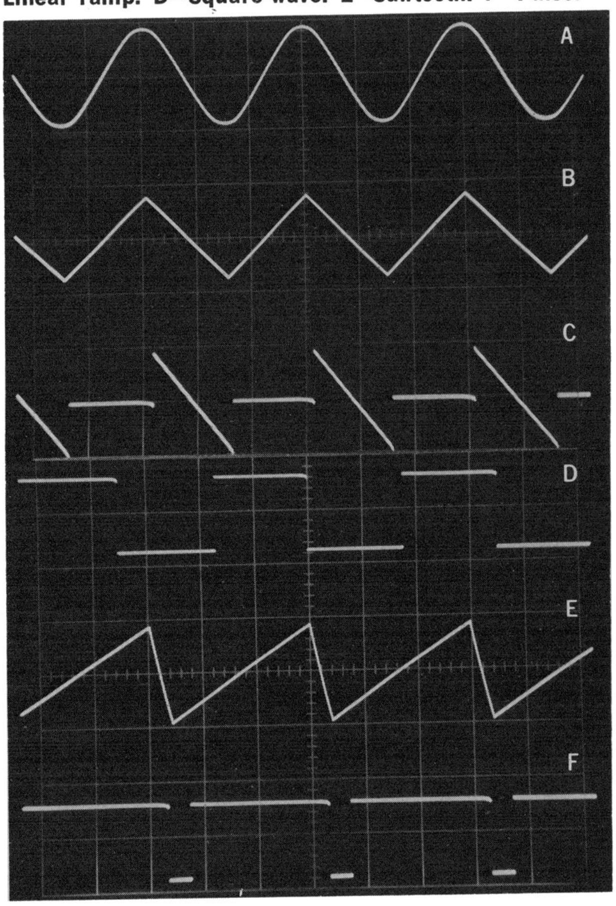
FIGURE 13. Distortion vs. frequency for sinusoidal output.



XR-205 performance characteristics

Supply voltage:
  Single supply, 8 to 26 volts
  Double supplies, ±5 to ±13 volts
Supply current: 10 mA
Operating temperature range: −55°C to +125°C
Frequency stability:
  Temperature, 300 ppm/°C
  Power supply, 0.2 percent per volt
Frequency range:
  Sine wave and square wave, 0.1 Hz to 5 MHz
  Triangle and ramp, 0.1 Hz to 500 kHz
Frequency sweep range: 10 to 1
Sweep (FM) nonlinearity: < 0.5 percent for 10 percent deviation
Output swing:
  Single-ended, 3 volts peak to peak
  Differential, 6 volts peak to peak
Output impedance:
  With buffer stage, 50 ohms
  Without buffer stage, 4000 ohms
Output amplitude control range: 60 dB
Sinusoidal output distortion: < 2.5 percent (THD)
Triangular, ramp, and sawtooth outputs:
  Nonlinearity, 1 percent for f_0 < 200 kHz
Square-wave output:
  Amplitude, 3 volts
  Duty cycle, 50 percent (±3 percent), adjustable from 20 to 80 percent
Modulation capability (all waveforms):
  AM, FM, FSK, PSK, tone burst

FIGURE 14. Basic periodic waveforms from monolithic waveform generator. A—Sinusoidal. B—Triangular. C—Linear ramp. D—Square-wave. E—Sawtooth. F—Pulse.



depending on the desired output waveform; and the output of the buffer amplifier is connected to ground or to $-V_{EE}$ through load resistor R_L.

The circuit of Fig. 8 was designed to take full advantage of the close matching and tracking properties of integrated components. For this reason, a differential rather than single-ended circuit configuration is used for each of the circuit blocks. This approach also provides a high common-mode range for the circuit and facilitates its operation over a range of supply voltages from ±5 volts to ±13 volts.

The waveform generator circuit was integrated on a 78-mil-square (2-mm-square) monolithic chip of silicon, shown in the photomicrograph of Fig. 10. A generalized circuit connection diagram for the XR-205 is shown in Fig. 11. Various output waveforms directly available from the circuit are also identified in the figure, but the buffer amplifier section is not explicitly shown. The capacitor C_0 across terminals 14 and 15 sets the free running frequency of the oscillator, as shown in Fig. 12. The output across pins 1 and 2 is either triangular or sinusoidal, depending on the setting of the resistor R_E connected across pins 7 and 8. The potentiometer R_q controls the dc bias applied to the modulation input. It

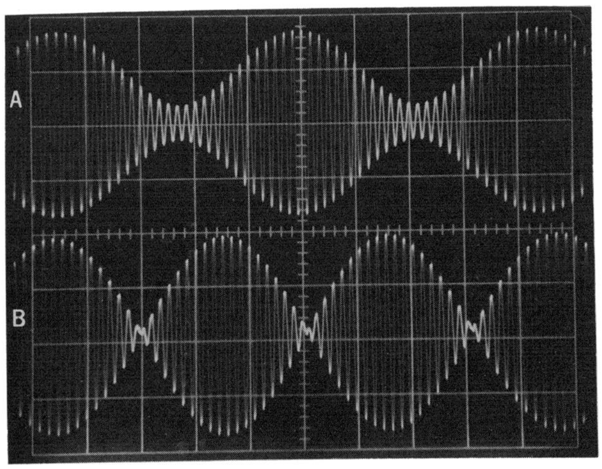
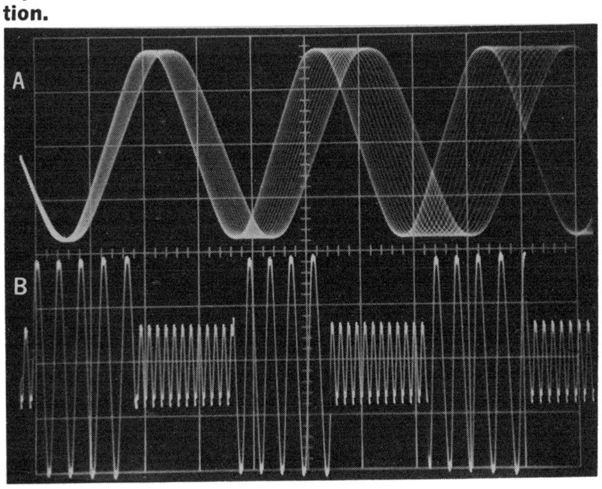


FIGURE 15. Amplitude-modulated waveforms. A—Double-sideband. B—Suppressed-carrier.

FIGURE 16. A—Linear frequency modulation. B—Square-wave simultaneous amplitude/frequency modulation.



can be used to set the output signal amplitude in accordance with the modulator section transfer characteristics shown in Fig. 6. The output frequency can be voltage-controlled or modulated by applying a control signal to the sweep input terminal (pin 13), as shown in Fig. 9.

The harmonic content of the sinusoidal output has been found to be 2.5 percent or less and relatively independent of the modulation input and frequency of operation. Figure 13 shows the harmonic content of the output waveform as a function of frequency. Typical performance characteristics of the monolithic waveform generator are listed in the box on page 39.

Figures 14 through 18 show some of the output waveforms available from the monolithic generator circuit. The waveforms in Fig. 14 correspond to the six basic periodic waveshapes generated by the XR-205 circuit. The first four waveforms (sinusoidal, triangular, ramp, and square) are directly available from the circuit connection of Fig. 11. The asymmetrical waveforms, such as the sawtooth and pulse outputs, can be derived from the triangular and square-wave outputs by offsetting the oscillator duty cycle. In the circuit connection diagram of Fig. 11 this can be achieved by connecting a 1-kilohm resistor between terminals 13 and 14.

Figure 15 shows the amplitude-modulated output waveforms for double-sideband and suppressed-carrier modes of operation. In suppressed-carrier AM generation, the circuit offers a carrier suppression of approximately 50 dB for frequencies to 5 MHz. The linear frequency-modulated waveform of Fig. 16A can be obtained by applying a modulation input to the sweep terminal. The nonlinearity of the FM characteristic is less than ± 0.5 percent for ± 10 percent FM deviation. Simultaneous AM/FM capabilities of the circuit also permit generation of the complex waveforms of Figs. 16B and 17A by application of the same modulating signal to both the AM and FM terminals (pins 3 and 13) shown in Fig. 11.

The oscillator can be on/off-keyed for tone-burst generation by applying a positive pulse of greater than 3 volts to the sweep terminal. A typical tone-burst output waveform obtained in this manner is displayed in Fig. 17B. The phase-shift characteristics of the doubly balanced modulator section (see Fig. 6) of the generator can be used for PSK modulation of the output. Applying a pulse input between terminals 3 and 4 of Fig. 11 causes a 180-degree phase reversal of the output waveform, as shown in Fig. 18.

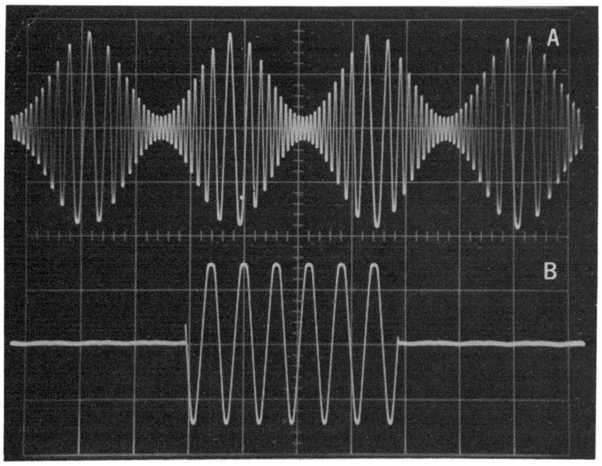
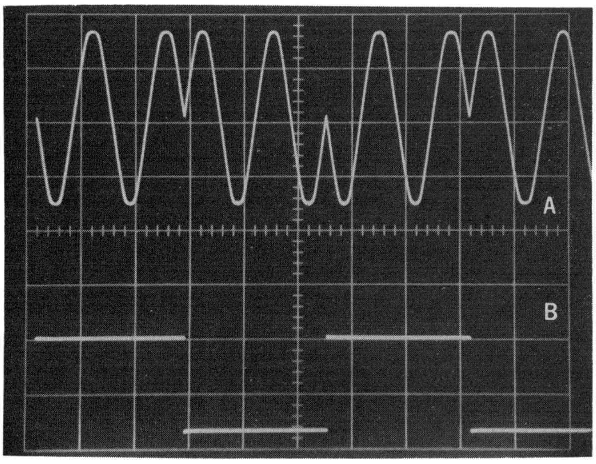


FIGURE 17. A—Sinusoidal amplitude/frequency modulation. B—Sinusoidal tone-burst generation.

FIGURE 18. Sinusoidal phase-shift keyed output. A—PSK output signal. B—Keying pulse.



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