Clock or square wave generators

How to use transistors, op-amps and 555 timers to make a variety of square wave or 'clock' generator circuits.

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THE 'SQUARE WAVE' generator is one of the most basic circuit blocks used in modern electronics. It can be used for 'flashing' LED indicators, for generating audio tones, or for 'clocking' logic or counter/divider circuitry, etc. The generators themselves may produce either symmetrical or non-symmetrical waveforms, and may be of either the free-running or the 'gated' type.

Square wave generator circuits are quite easy to design, and may be based on a wide range of semiconductor technologies, including the humble bipolar transistor, the op-amp, the 555 timer chip or on CMOS logic elements, etc. In this month's edition we'll confine our discussion to designs based on the transistor, the op-amp and the 555; next edition we'll continue the subject by showing 22 different CMOS-based square wave generator circuits!

Transistor astables

One of the easiest and cheapest ways of generating repetitive square and rectangular waveforms is to use the basic two-transistor astable multivibrator circuit shown in Figure 1. A major advantage of this rather old-fashioned transistor circuit is that it can quite happily operate from supply voltages as low as 1.5 volts or, with a slight modification, from supply voltages up to several tens of volts.

The Figure 1 circuit acts essentially as a self-oscillating regenerative switch, in which the on and off periods of the circuit are controlled by the C1-R1 and C2-R2 time constants. If these time constants are equal (C1=C2 and R1=R2), the circuit acts as a square wave generator and operates at a frequency of approximately

$$1/(1.4\,C1\,R1)$$

Thus the frequency can be decreased by raising the values of C1-C2 or R1-R2, or vice versa. The frequency can be made variable by using twin-gang variable resistors (in series with 10k limiting resistors) in place of R1 and R2.

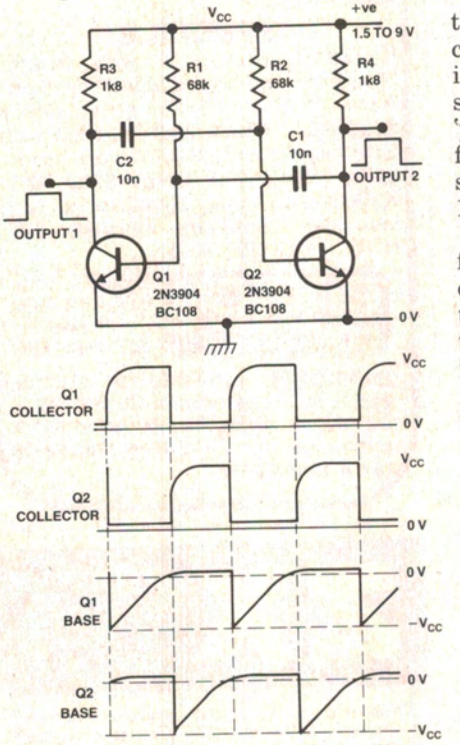

Figure 1. **Circuit and relevant waveforms of basic 1 kHz transistor astable multivibrator.**

Outputs can be taken from either collector of the Figure 1 circuit, and the two outputs are in antiphase. The operating frequency of the circuit is substantially independent of supply rail values in the range 1.5 to 9 volts. The upper supply voltage limit is set by the fact that, as the transistors switch regeneratively at the end of each half-cycle, the base-emitter junction of the transistor is reverse-biased by an amount roughly equal to the supply voltage. Consequently, if the supply voltage exceeds the reverse base-emitter breakdown voltage of the transistor (typically about 9 volts), the timing operation of the circuit will be upset. This snag can be overcome by using the circuit modification shown in Figure 2.

Here, a 1N4148 diode is wired in series with the base input terminal of each transistor and effectively raises the reverse base-emitter breakdown voltage of each transistor to about 80 volts. The maximum supply voltage of the circuit is then limited only by the collector-emitter breakdown characteristics of the transistors, and may be several tens of volts. In practice, the 'protected' circuit of Figure 2 gives a frequency variation of only 2% when the supply voltage is varied from 6 V to 18 V.

The leading edges of the output waveforms of the Figure 1 and Figure 2 circuits are slightly rounded. The lower the values of R1 and R2 become relative to collector resistors R3 and R4, the worse this rounding becomes. Conversely, the larger the values of R1 and R2 relative to R3 and R4, the better the wave shape will be. The maximum permissible values of R1 and R2 are equal to the products of transistor current gain (say 90) and the R3 (or R4) values (1k8 in this case), so the maximum possible values of R1 and R2 are 162k in the Figure 1 and Figure 2 circuits.

The rounding of the leading edges of the basic astable circuit occurs because the collector voltage of each transistor is prevented from rising immediately to the positive rail voltage as the transistor turns off, because of loading by its cross-coupled timing capacitor. This deficiency can be overcome, and excellent square waves obtained, by effectively disconnecting the capacitor from the collector of its transistor as it turns off, as in the 1 kHz generator of Figure 3. Here, D1 and D2 are used to disconnect the timing capacitors at the moment of regenerative switching. The main time constants of the circuit are

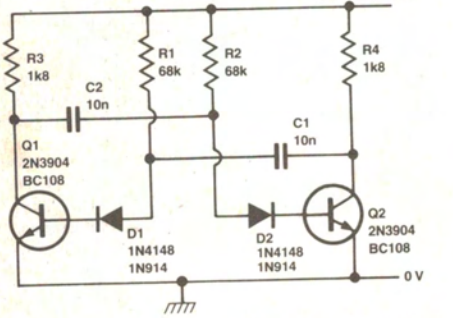

Figure 2. **This version of the 1 kHz astable has frequency correction applied via D1 and D2**

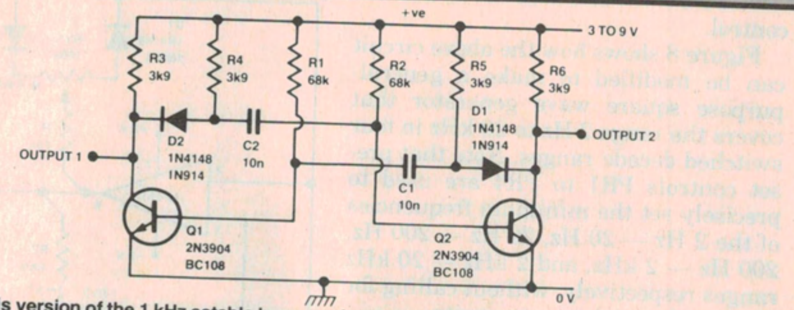

Figure 3. **This version of the 1 kHz astable has waveform correction applied via D1 and D2 and produces excellent square waves.**

again determined by C1-R1 and C2-R2. The effective collector loads of Q1 and Q2 are equal to the parallel resistances of R3-R4 and R5-R6 respectively.

Operation of the basic astable multivibrator relies on slight imbalances of the transistor characteristics, so that one transistor turns on slightly faster than the other when power is first applied. If the voltage to the circuit is applied by slowly increasing it from zero volts, both transistors may turn on simultaneously, in which case oscillation will not occur. This snag can be overcome by using the sure-start circuit of Figure 4, in which the timing resistors are connected to the transistor collectors in such a way that only one transistor can ever be turned on at a given moment.

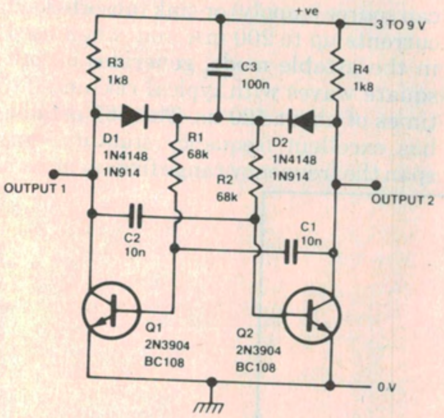

Figure 4. **The 1 kHz astable with 'sure-start' facility.**

The transistor astable circuits we have looked at so far are designed to give a symmetrical output waveform, with a 1:1 mark-to-space ratio. A non-symmetrical waveform can be obtained by simply making one set of astable time-constant components larger than the other. Figure 5a shows the connections for making a fixed-frequency (about 1100 Hz) variable mark-to-space ratio waveform generator, in which the ratio can be fully varied over the range 1:10 to 10:1.

The leading edges of the output waveforms of the above circuit may be objectionably rounded for some applications when the mark-to-space control is set to its extreme positions. Also, the circuit may be difficult to start if the supply voltage is applied to the circuit slowly. Both of these snags can be overcome by using the connections of Figure 5b, in which the circuit is fitted with sure-start and waveform-correction diodes.

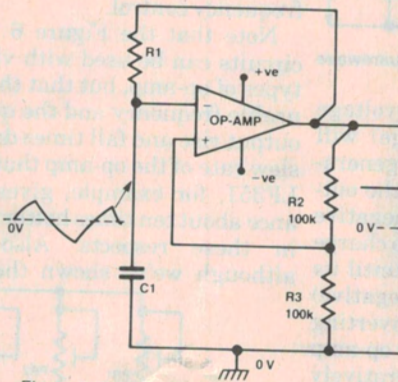

Figure 6. **Basic op-amp relaxation oscillator.**

Op-amp generators

Good square waves can be generated by using a fast op-amp, such as the LF351, in the basic relaxation oscillator configuration shown in Figure 6. This circuit requires the use of dual power supplies and, because of the slew-rate limitations of op-amps, its output waveform rise and fall times are not as good as those obtained from transistor, 555, or CMOS astables. The op-amp circuit has, however, some distinct advantages over these alternative types of square wave generator; specifically, it has excellent frequency stability and the waveform can be varied over a wide range by altering any *one* of its four passive component values.

The basic operation of the Figure 6 cirucit is fairly easy to follow. The output of the op-amp alternatively switches between the positive and negative supply rail values and thus applies a positive or negative 'reference' voltage to the non-inverting terminal of the op-amp, this reference voltage being a fixed fraction or ratio (determined by the R2-R3 ratios) of the supply voltage.

Suppose initially that C1 is discharged and the op-amp output has just switched positive. In this case C1 will charge positively via R1 until its voltage reaches the positive reference value on the non-inverting terminal of the op-

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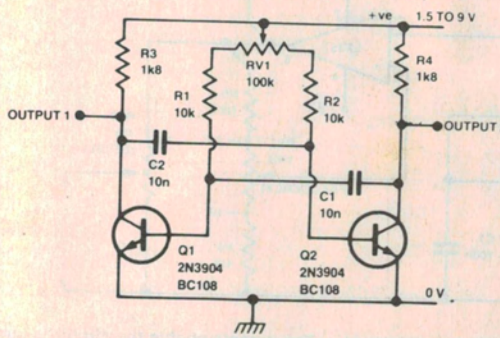


Figure 5a. **Basic variable M/S ratio astable operating at about 1100 Hz.**

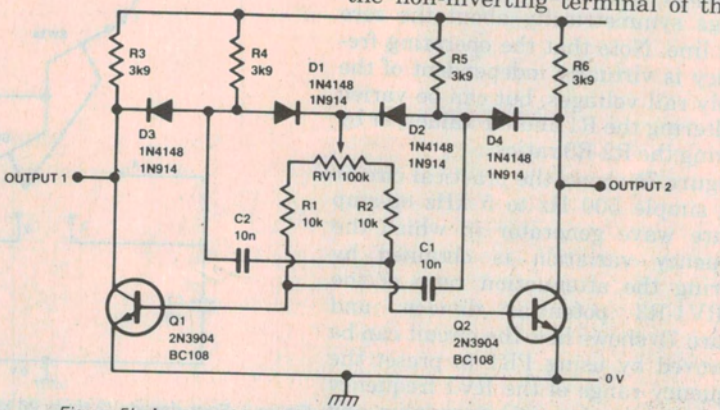


Figure 5b. **Improved version of variable M/S ratio astable with waveform correction and sure-start facility.**

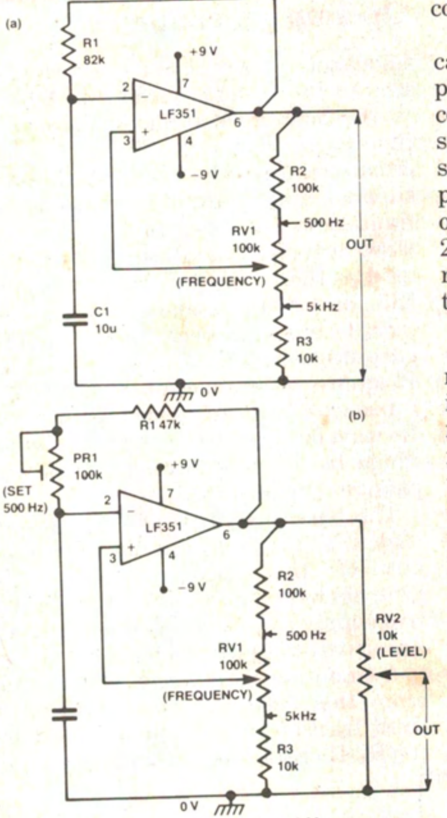


Figure 7. **(a) Simple 500 Hz to 5 kHz squarewave generator and (b) an improved version.**

amp, at which point the op-amp voltage (and thus the reference voltage) will start to fall and thus initiate a regenerative switching action in which the output switches abruptly to the negative rail voltage. C1 will then start to charge in a negative direction via R1 until its voltage reaches the new (negative) reference value on the non-inverting terminal, at which point the op-amp output will again switch regeneratively high and initiate a new action in which the whole sequence repeats itself.

The action of the op-amp circuit is such that a symmetrical square wave is developed at the output of the op-amp, and a non-linear triangle waveform is developed across C1; each waveform swings symmetrically about the zero volts line. Note that the operating frequency is virtually independent of the supply rail voltages, but can be varied by altering the R1 and C1 values, or by altering the R2-R3 ratios.

Figure 7a shows the practical circuit of a simple 500 Hz to 5 kHz op-amp square wave generator in which the frequency variation is obtained by altering the attenuation ratio of the R2-RV1-R3 potential divider, and Figure 7b shows how the circuit can be improved by using PR1 to preset the frequency range of the RV1 frequency control to a precise minimum value, and by using RV2 as an output amplitude control.

Figure 8 shows how the above circuit can be modified to make a general-purpose square wave generator that covers the range 2 Hz to 20 kHz in four switched decade ranges. Note that preset controls PR1 to PR4 are used to precisely set the minimum frequencies of the 2 Hz — 20 Hz, 20 Hz — 200 Hz, 200 Hz — 2 kHz, and 2 kHz — 20 kHz ranges respectively, without calling for the use of precision components.

Finally, Figure 9 shows how the basic relaxation oscillator circuit can be modified so that it provides both a variable frequency and a variable mark-to-space ratio output. The mark-to-space ratio is variable via RV1, and the circuit action is such that C1 alternately charges positively via R1-D1 and the left-hand side of RV1 and charges negatively via R1-D2 and the right-hand side of RV1. The mark-to-space ratio is variable over the range 11:1 to 1:11, and the frequency is variable over the approximate range 650 Hz to 6.5 kHz via RV2; varying the mark-to-space ratio setting causes only slight interaction with the frequency control.

Note that the Figure 6 to Figure 9 circuits can be used with virtually any types of op-amp, but that the maximum usable frequency and the quality of the output rise and fall times depend on the slew rate of the op-amp that is used; the LF351, for example, gives a performance about ten times better than the 741 in these respects. Also note that although we've shown the circuits as being powered from 9 volt split supplies, they can in fact be powered from any split supplies in the range 5 to 18 V.

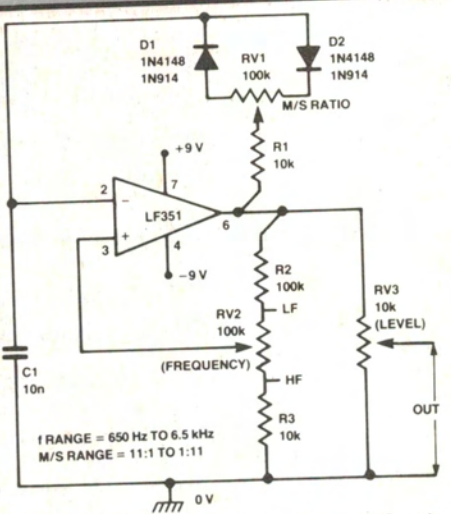


Figure 9. **Variable frequency, variable M/S ratio generator.**

555 astables

The IC known as the '555 timer' makes an excellent square wave generator when used in the astable mode. The device is readily available, inexpensive, and is housed in an 8-pin dual-in-line (DIL) plastic package. It can be powered by any supply in the range 4.5 to 15 volts, has a low-impedance output that can source (supply) or sink (absorb) load currents up to 200 mA and, when used in the astable mode, generates output square waves with typical rise and fall times of about 100 ns. The 555 astable has excellent frequency stability, can span the frequency range from near zero

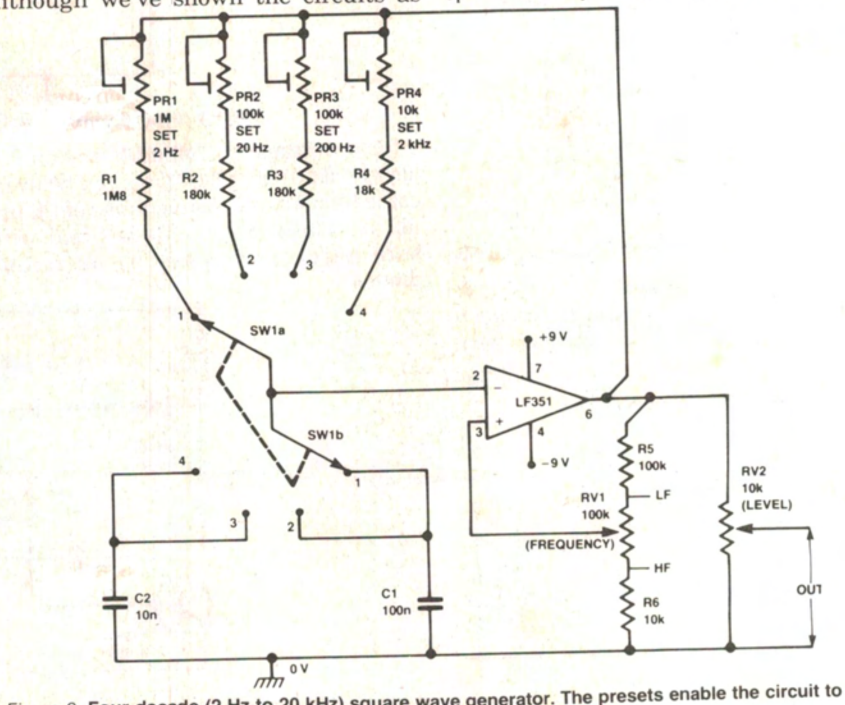
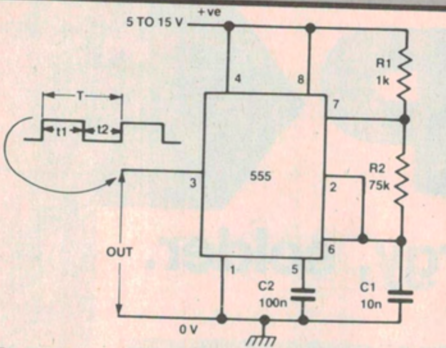


Figure 8. **Four-decade (2 Hz to 20 kHz) square wave generator. The presets enable the circuit to use a single calibrated frequency scale.**



$$t1 = 0.7(R1 + R2)C1$$
$$t2 = 0.7\,(R2)C1$$
$$T = 0.7(R1 + 2R2)C1$$
$$f = \frac{1.44}{(R1 + 2R2)C1}$$

IF R2 >> R1:

$$t1 = 0.7 \times R2 \times C1$$
$$t2 = 0.7 \times R2 \times C1$$
$$T = 1.4 \times R2 \times C1$$
$$f = \frac{0.72}{R2 \times C1}$$

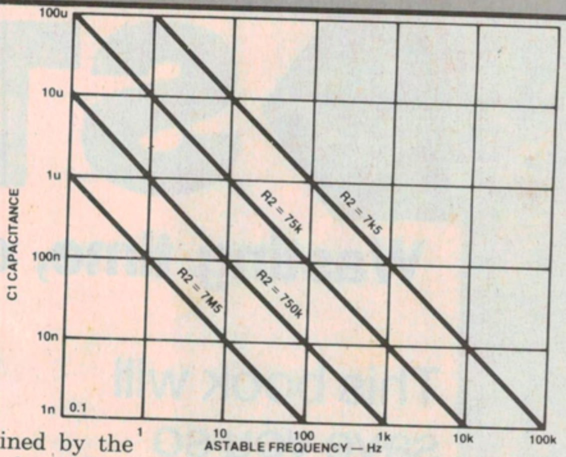


Figure 10. **(a) Basic circuit of a 1 kHz 555 astable with design formulae. (b) Approximate relationship between C1, R2 and f for the 555 astable when R2 is large relative to R1.**

to about 100 kHz, and its frequency and mark-to-space ratio can be accurately controlled with two external resistors and one capacitor.

Figure 10a shows the practical circuit of a basic 1 kHz 555 astable, together with the formulae that define the timing of the circuit. The circuit operation is such that C1 first charges exponentially via the series R1-R2 combination until eventually its voltage rises to two-thirds of the supply voltage, at which point a regenerative switching action takes place and C1 starts to discharge exponentially via R2 until eventually its voltage falls to one-third of the supply voltage. At this point a second regenerative switching action takes place and C1 starts to re-charge towards two-thirds of the supply voltage via R1-R2, and the whole sequence repeats. C2 is used in this circuit (and those that follow) to decouple the internal circuitry of the 555 chip from the effects of supply line transients.

Note that the operating frequency of the above circuit is virtually independent of the supply voltage value, and that both the mark-to-space ratio and the frequency are determined by the R1-R2-C1 values. Also note that if R2 is large relative to R1, the operating frequency is determined mainly by the R2 and C1 values and that an almost symmetrical output waveform is generated. The graph of Figure 10b shows the approximate relationship between frequency and the C1-R2 values under the above condition. In practice, the R1 and R2 values can be varied from about 1k to 10M.

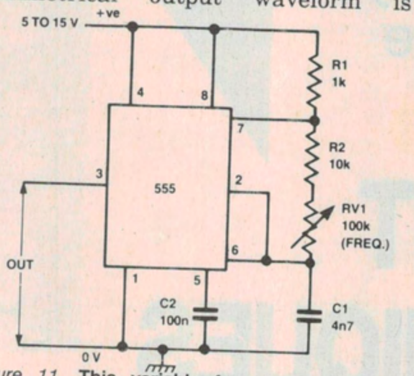


Figure 11. **This variable frequency generator covers 1.4 kHz to 15 kHz.**

The basic Figure 10a circuit can be modified in a number of ways. Figure 11, for example, shows how it can be made into a variable frequency square wave generator by replacing R2 with a fixed and a variable resistor in series. With the component values shown, the frequency can be varied over the approximate range 1.4 kHz to 15 kHz via RV1.

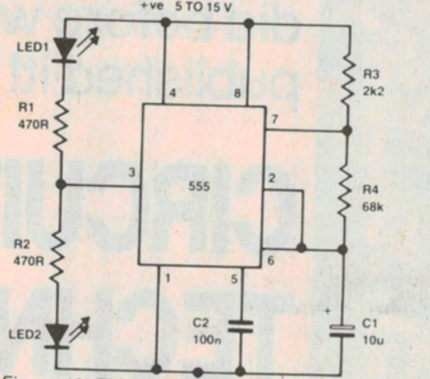


Figure 12. **This two-LED flasher operates at just under 1 Hz. The LEDs flash alternately.**

Figure 12 shows how the circuit can be used as a two-LED 'flasher' unit, in which one LED turns off as the other turns on, and vice versa. The circuit▶

circuit file

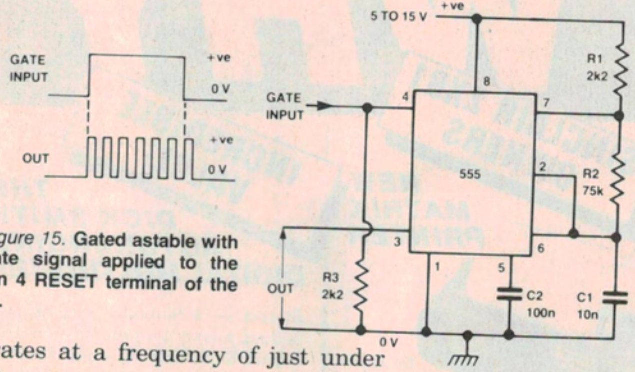


Figure 15. **Gated astable with gate signal applied to the pin 4 RESET terminal of the IC.**

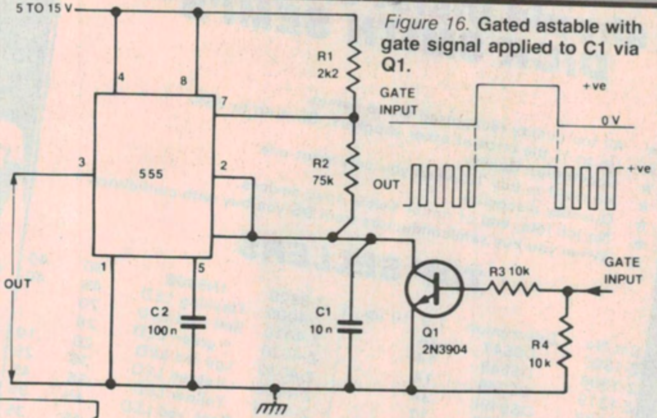


Figure 16. **Gated astable with gate signal applied to C1 via Q1.**

operates at a frequency of just under 1 Hz.

Figure 13 shows how the circuit can be modified so that its mark and space periods are independently variable over the approximate range 15 us to 1.5 ms.

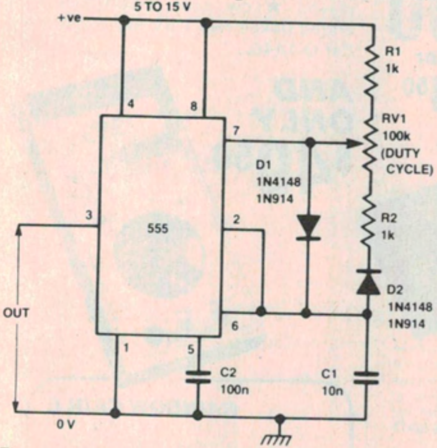


Figure 13. **Astable with mark and space periods independently variable over about 15 us to 1.5 ms.**

Here, timing capacitor C1 alternately charges via R1-RV1-D1 and discharges via RV2-R2-D2.

Figure 14 shows how the circuit can be modified so that it acts as a fixed-frequency square-wave generator with a mark-to-space ratio or duty cycle that is fully variable from 1% to 99% via RV1. Here, C1 alternately charges via R1 and the top half of RV1 and D1, and discharges via D2-R2 and the lower half of RV1. Note that the sum of these two timing periods is virtually constant, so the operating frequency is almost independent of the setting of RV1.

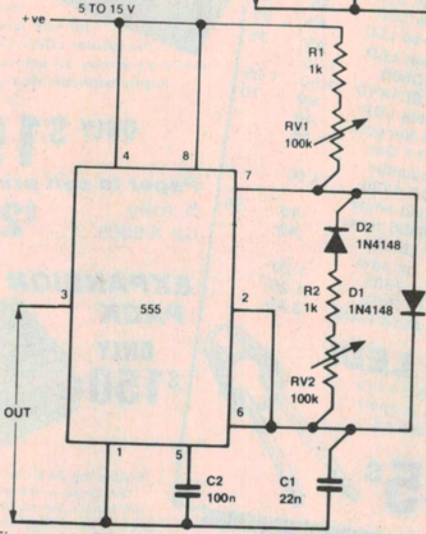


Figure 14. **555 astable with duty cycle variable from 1% to 99%. Frequency is almost constant at about 1 kHz.**

The 555 astable circuit can be gated on and off (enabled or disabled) either by applying a gate signal to pin 4 or by disabling or enabling the main timing capacitor via a transistor switch.

Figure 15 shows how the circuit can be gated via the pin 4 (reset) terminal. The characteristic of this terminal is such that if the terminal is biased above a nominal 0.7 volts, the astable is enabled, but if it is biased below 0.7 volts by a current greater than 100 uA (by taking pin 4 to ground via a resistance less than 7k, for example) the astable is disabled and its output is grounded. Thus in the Figure 15 circuit the astable can be turned on by applying a high or logic 1 signal to pin 4, or off by applying a zero or logic 0 signal to pin 4.

Finally, to complete this month's look at square wave generator circuits, Figure 16 shows how the 555 astable can be gated on and off via a transistor wired across the main timing capacitor, C1. Here, with zero gate drive applied, Q1 is cut off and the astable is free to operate in the normal way, but when a high gate signal is applied, Q1 is driven on and discharges C1, thus disabling the astable. Note that the output of this circuit is driven high when the astable is disabled in this way. ●