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George

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[54] **TRIANGLE WAVE GENERATOR HAVING DIRECT TUNNEL DIODE SWITCH CONTROL**

[75] Inventor: **Richard E. George**, Anaheim, Calif.

[73] Assignee: **Interstate Electronics Corporation**, Anaheim, Calif.

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[52] **U.S. Cl.** **307/228**, 307/322, 328/181, 328/183

[51] **Int. Cl.** **H03k 4/08**

[58] **Field of Search** 307/228, 322; 328/181, 328/183, 185

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Primary Examiner—Stanley D. Miller, Jr.
Attorney, Agent, or Firm—Knobbe, Martens, Olson, Hubbard & Bear

[57] **ABSTRACT**

A tunnel diode is used to directly drive a current switch for controlling the current supplied to the integrator of a triangle wave generator, a latching circuit being connected to maintain the current switch on the on or off state between successive driving signals from the tunnel diode.

15 Claims, 6 Drawing Figures

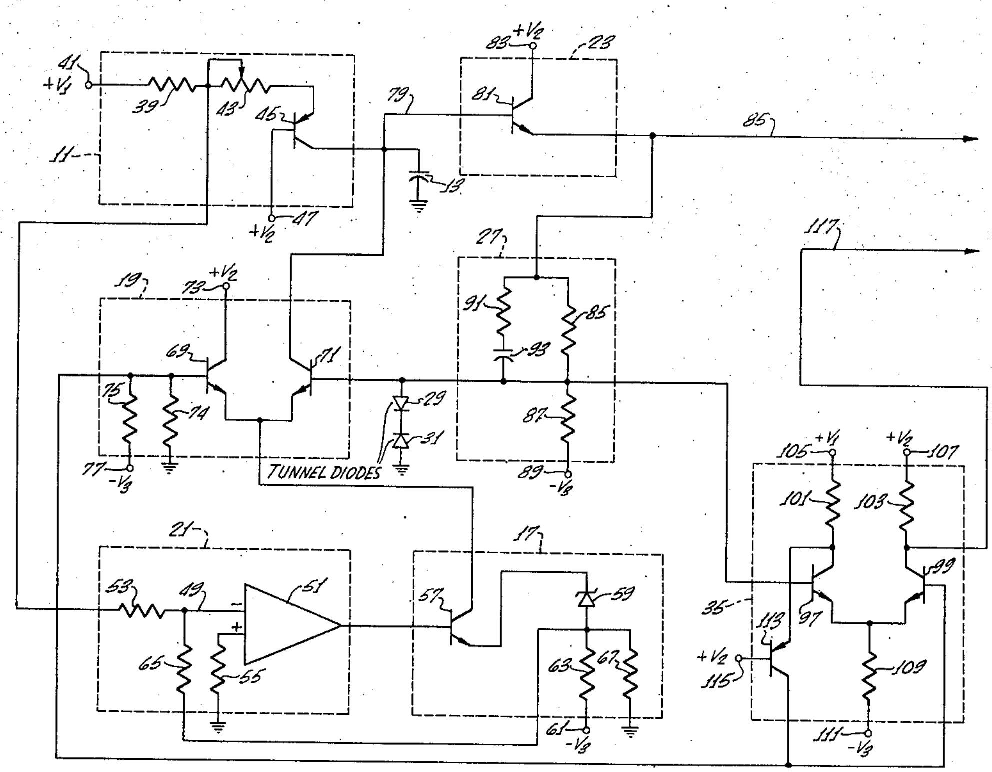

FIG. 1.

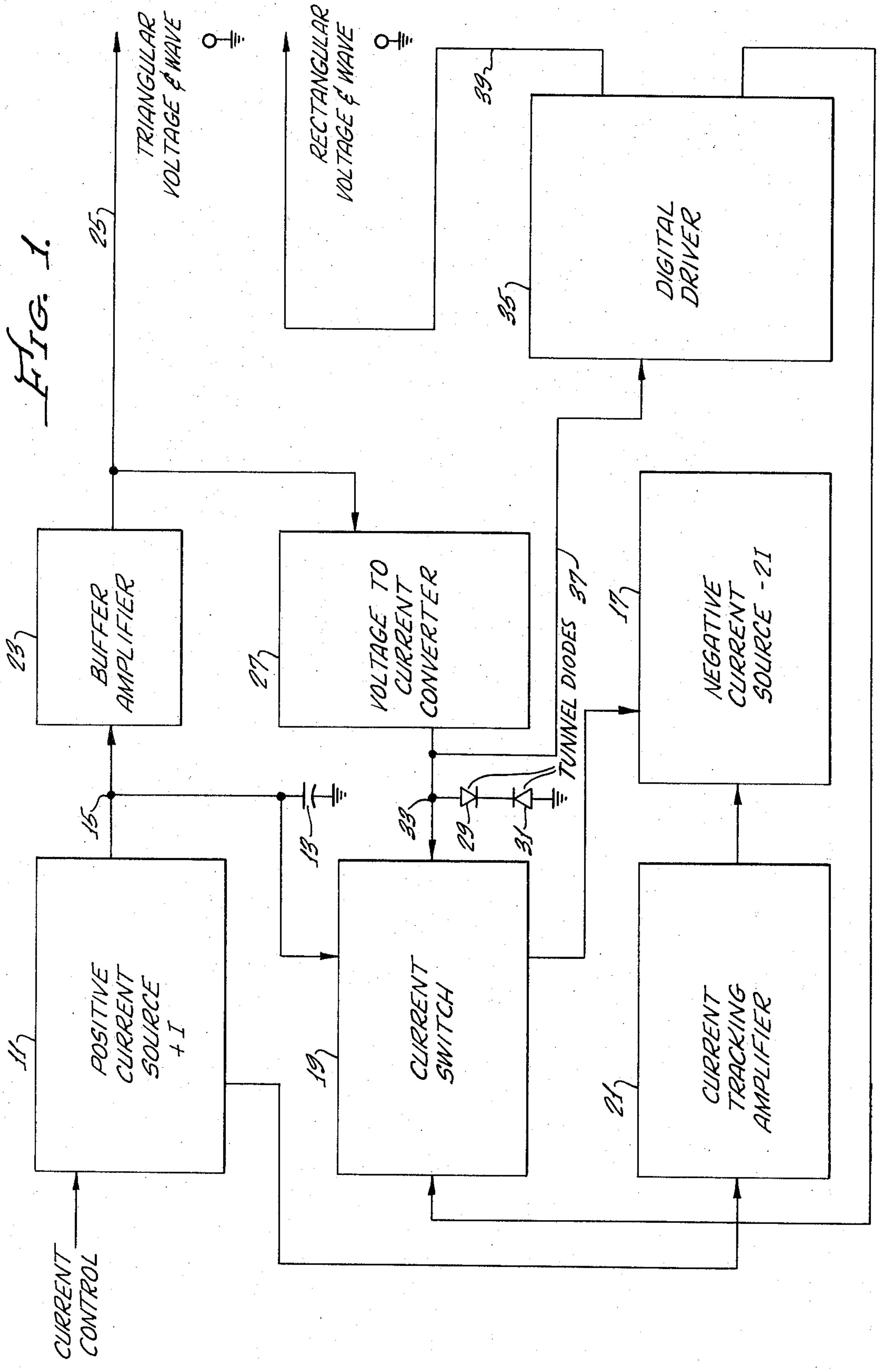
TRIANGULAR VOLTAGE WAVE
RECTANGULAR VOLTAGE WAVE
25
39
DIGITAL DRIVER
35
BUFFER AMPLIFIER
23
VOLTAGE TO CURRENT CONVERTER
27
TUNNEL DIODES
37
NEGATIVE CURRENT SOURCE -2I
17
15
13
33
29
31
POSITIVE CURRENT SOURCE +I
11
CURRENT SWITCH
19
CURRENT TRACKING AMPLIFIER
21
CURRENT CONTROL

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FIG. 2.

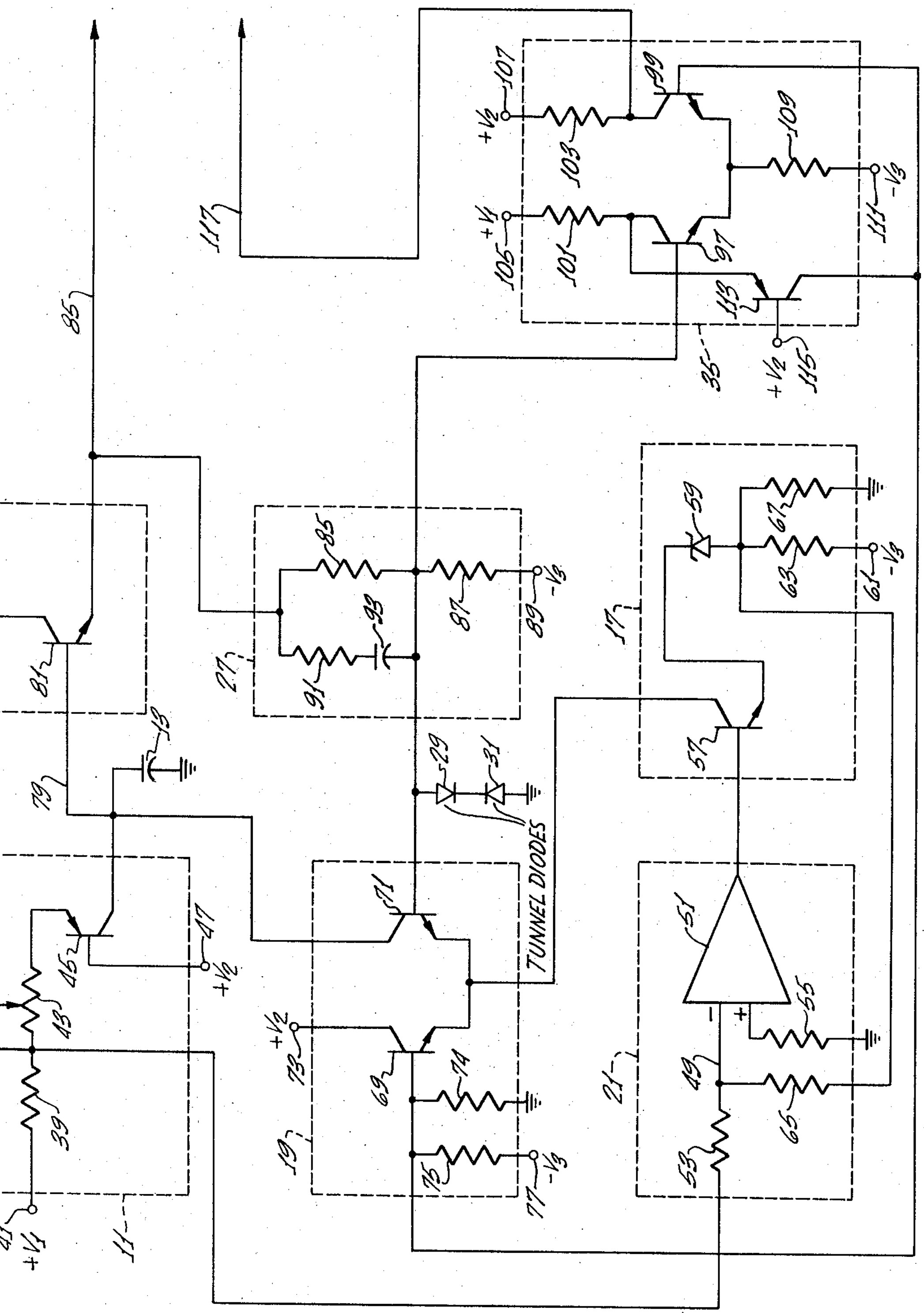


FIG. 3a.

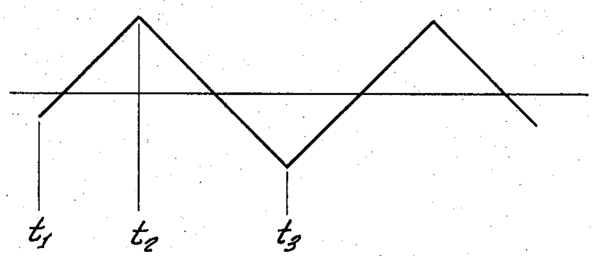


FIG. 3b.

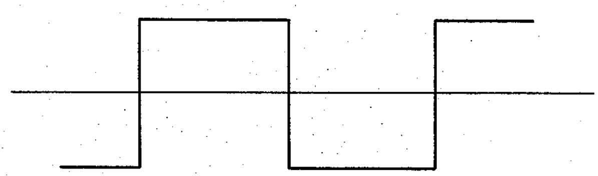


FIG. 3c.

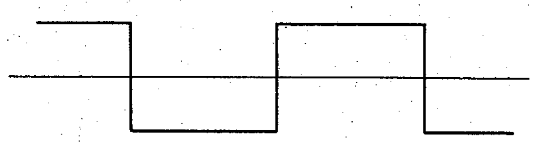
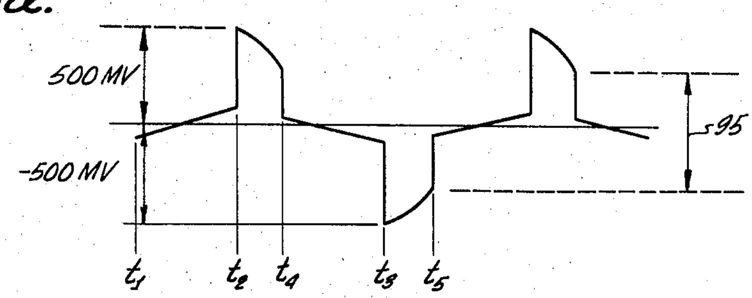


FIG. 3d.



TRIANGLE WAVE GENERATOR HAVING DIRECT TUNNEL DIODE SWITCH CONTROL

BACKGROUND OF THE INVENTION

This invention relates to triangle wave generators, and more specifically to a circuit for controlling such circuits using a tunnel diode directly coupled to the primary current switch to increase the frequency at which the triangle wave generator will satisfactorily operate.

It has been common in the prior art to generate triangle waveforms by alternately connecting positive and negative sources of current to an integrating device such as a capacitor. As the positive current source charges the capacitor, the voltage across the capacitor, assuming a regulated current source, will increase as a ramp function. It has likewise been common to monitor the voltage across the integrating device and to connect a negative current source when the capacitor voltage reaches a desired peak level. The capacitor voltage will then decrease as a ramp function from this peak voltage and is then commonly monitored to reapply the positive current source when the voltage across the capacitor reaches a desired negative peak level.

Existing triangle wave generators have used the desirable characteristics of tunnel diodes to monitor the voltage level across the capacitor for switching the current sources. Typically, a voltage-to-current converter has been connected across the integrating device and the current from this converter has been applied to a forward biased tunnel diode. Below a predetermined current level the tunnel diode exhibits a relatively low impedance. When, however, the voltage across the integrating device reaches a predetermined level, the current through the tunnel diode reaches a threshold level which causes the tunnel diode to immediately exhibit a relatively high impedance. This impedance shift within the tunnel diode has been used in prior art devices to control a bistable device which is then in turn used to drive the current switch for controlling the current to the integrating device. This intermediate bistable device has been thought in the past to be a necessary element of such triangle wave generators since the tunnel diode exhibits a disadvantageous characteristic as the current is reduced following the voltage wave peak. Thus, if the tunnel diode were used to directly drive the main current switch, when the tunnel diode reached its second threshold level, that is, the current level at which it switches from a relatively high impedance back to a relatively low impedance, the effect would be to again switch the current sources. This second threshold level, that is, the threshold level of the tunnel diode as the current through the diode decreases, is far less accurate than the threshold of the diode as the current therethrough increases. Thus, in the prior art circuits, it has been common to use a pair of tunnel diodes, one for sensing the positive peak level of the triangle wave and the other for sensing the negative peak level of the wave, and to use these tunnel diodes to drive a bistable element such as a flip-flop for controlling the current switch in each direction, In this way the second threshold current of each of the tunnel is ignored by the bistable element and only the precisely determinable threshold of each of the tunnel diodes is used to control the current switch.

This use of an intermediate bistable element necessarily introduces time delay between the tunnel diode threshold and the activation of the current switch. At relatively low frequencies, this time delay is inconsequential and does not interfere with satisfactory operation of the triangle wave generator. However, as the frequency is increased, and particularly, for example, above a frequency of approximately 20 MHz, the time delay of the bistable device distorts the triangle wave. Thus, particularly in a variable frequency generator, it can be seen that the amplitude of the trinagle wave will exceed the desired amplitude as the frequency of the generator is increased since the current source will not be switched until after the desired peak voltage is reached. Furthermore, at even higher frequencies when the time delay within the bistable device approximates one half the period of the triangle wave, it becomes impossible to use this system at all. For this reason it has been typical in the art to expect an upper frequency limit from triangle wave generators in the range of approximately 20 MHz.

SUMMARY OF THE INVENTION

The present invention overcomes this inherent frequency limitation by directly driving the switch which controls the current source from the tunnel diode. As explained previously, this can be accomplished only if the unpredictable second threshold of the tunnel diode is ignored by the circuit. For this reason, a latching circuit is incorporated which maintains the main current switch in an on or off condition between subsequent thresholding of a forward and reverse biased tunnel diode pair.

A voltage-to-current converter is utilized to monitor the voltage across an integrating device and to convert this voltage to a proportional current level. This current level is applied to a bipolar tunnel diode pair which is connected directly to control the current switch. In addition, a latching circuit is connected to the tunnel diodes so that when either of the tunnel diodes passes through its first threshold the latching circuit will activate to maintain the current switch in its new stage until the other tunnel diode causes a reversal in the current switch state and a reversal of state in the latching circuit. This circuit configuration enables the tunnel diodes to be directly connected to the current switch so that the triangle wave generator will satisfactorily operate at frequencies about 100 MHz.

These and other advantages of the present invention are best understood through a reference to the drawings, in which:

FIG. **1** is a block diagram of the triangle wave generator of the present invention;

FIG. **2** is a schematic diagram showing the circuitry used in the preferred embodiment of the present invention; and

FIGS. **3*a*–3*d*** are diagrams showing the waveforms present on various components of the circuit of FIG. **2.**

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring initially to FIG. **1,** a positive current source **11** is coupled directly to a capacitor **13** which operates as the integrating device in the present circuit. As current flows from the positive current source **11** into the capacitor **13,** the voltage across the capacitor **13** which appears at a point **15** will increase as a linear function with time. A negative current source **17** having a current which is twice the current of the source **11** is additionally connected to the integrating device **13** through a current switch **19.** As is well known in the triangle wave generating art, the current switch **19** controls only the current from the negative current source **17.** However, since the current source **17** is at twice the current level of the current source **11,** it will be immediately recognized that when the current switch **19** is in an open circuit configuration the current source **11** will supply current to the integrating device **13** at a level +I. However, when the current switch **19** is in a closed circuit configuration the negative current source **17** will draw current through the switch **19** at a rate of −2I. One half of this current is supplied by the positive current source **11** but the other half of the current must be supplied by drawing current from the intergrating device **13.** Thus, by simply controlling current flow in one direction through the current switch **19,** it is well known that the integrating device **13** may be alternately charged and discharged so that the voltage at the point **15** alternately increases linearly with time or decreases linearly with time to form a triangular voltage waveform. In the preferred embodiment shown in FIG. **1** wherein the current source **17** has a current level which is twice that of the current source **11,** the rate of increase of the voltage at the point **15** with time when the current switch **19** is open is precisely the same as the rate of decrease of voltage at the point **15** when the current switch **19** is closed.

In the present embodiment, a current tracking amplifier **21** is directly coupled to the current source **11** and controls the current source **17** to operate at precisely twice the level of the current source **11,** so that a true triangle voltage wave will be produced at the point **15.** An amplifier **23** is connected to the point **15** and produces the triangle voltage wave output from the triangle wave generator on a line **25.** In addition, this triangular wave voltage is connected to a voltage-to-current converter **27** which is used to drive a pair of tunnel diodes **29** and **31.** These tunnel diodes **29** and **31** are used to monitor the current produced by the voltage-to-current converter **27** which is proportional to the triangular voltage wave on the line **25** for directly driving the current switch **19.** Thus, as current flows from the converter **27** through the tunnel diodes **29** and **31** to ground, the tunnel diode pair will exhibit a relatively low impedance until the threshold current level of the tunnel diode **29** is reached. At this point the impedance of the tunnel diode **29** will immediately increase and the voltage at a point **33** will immediately increase. This voltage at the point **33** is used to close the current switch **19,** thereby connecting the negative current source **17** to the integrating device **13** so that the voltage at the point **15** will begin to decrease from its positive peak level. In addition, the increased voltage level at the point **33** will drive a digital driver **35** through a line **37.** The digital driver **35** operates to change the bias levels on the current switch **19** so that, as the voltage at point **15** decreases and the current through the tunnel diode pair from the converter **27** similarly decreases, the thresholding of the tunnel diode **29** to its low impedance level will not change the state of the current switch **19.**

When the voltage at the point **15** reaches the desired negative peak level, the current from the voltage-to-current converter **27** will be in the negative direction, that is, current will flow from ground through the tunnel diode pair **29** and **31** into the voltage-to-current converter **27.** When this current reaches the threshold level of the tunnel diode **31,** the tunnel diode **31** will immediately exhibit a high impedance so that the voltage at the point **33** will immediately shift to a negative level. This shift drives the current switch **19** to an open circuit condition and, in turn, through the line **27,** drives the digital driver **35** to maintain a bias level on the current switch **19** which will hold the current switch **19** in this open circuit configuration until the tunnel diode **29** again passes through its threshold current level at the positive peak voltage of the waveform at the point **15.** The digital driver operates as a bistable element and therefore a rectangular voltage waveform is conveniently available on an output line **39.**

It can be seen, therefore, that the tunnel diode pair **29** and **31** directly controls the current switch **19** without the interposition of a bistable element which would introduce time delays between the thresholding of the tunnel diodes **29** and **31** and the activation of the current switch **19.** Since the bistable element is not connected directly in the control between the tunnel diodes **29** and **31** and the current switch **19,** a digital driver **35** is used as a latching circuit to maintain the current switch **19** in its on or off condition between successive thresholding of the tunnel diodes **29** and **31.**

Referring now to FIG. 2, the detailed circuitry of the preferred embodiment of the present invention will be described. The positive current source **11** for producing a current +I comprises an input resistor **39** which is connected to a positive voltage source +V**1** at a point **41.** The input resistor **39** is series connected to a potentiometer **43** which operates as a frequency adjustment. As will be readily recognized, the slope of the ramp signal produced in the integrating device **13** will depend upon the input current to the integrator **13.** Thus, by varying the current, a predetermined threshold level at which the circuit will close the current switch **19** will be reached more rapidly, and the frequency of the triangle wave generator will be increased. The output of the resistor **43** is connected to a common base transistor **45** having a relatively low input impedance and a high output impedance so that it operates as an impedance converter to drive the integrating device or capacitor **13** with a predetermined current +I. The base of the transistor **45** is connected to a reference voltage **30** V2 at point **47.**

The negative current source for producing a current of −2I could be constructed in a similar manner to the positive voltage source **11** by simply connecting a common base transistor to a negative voltage supply having a voltage equal to −V**1** through a resistor having half the resistance of the resistors **39** and **43,** so that a current level of −2I could be approximated. In the preferred embodiment, however, a current tracking amplifier **21** is used to assure that the −2I current is precisely controlled in response to the +I current produced by the positive current source **11** at all times. This is accomplished by connecting the inverting input **49** of an operational amplifier **51** to the junction of the resistors **39** and **43** through an input resistor **53.** The noninverting input of the operational amplifier **51** is connected to ground through a resistor **55.** The output of the operational amplifier **51** is connected to the base of the common base connected transistor **57** of the −2I current supply. The emitter of this transistor **57** is connected through a zener diode **59** which is used as a voltage level shifting device. The anode of the zener diode **59** is in turn connected to a negative voltage source

−V3 at a point **61** through a resistor **63**. The resistor **63** is selected to have precisely half the resistance of the resistor **39** so that if the voltage drop across the resistor **63** is maintained at an identical level with the voltage drop across the resistor **39**, the current through the zener diode **59** and the emitter-collector junction of the transistor **57** will be precisely twice the current which flows through the transistor **45** of the positive current source **11**. This is accomplished through a feedback loop through a resistor **65** which is connected to the junction of the anode of the zener diode **59** and an output resistor **67** which is connected to ground. The resistors **53, 65** and **67** are selected to have the same resistance. Thus, the combination of the amplifier **51** and the feedback loop creates a unity closed loop gain feedback amplifier. For a predetermined voltage drop across the resistor **39**, a corresponding voltage drop will be imposed across the resistor **63** by the operational amplifier **51** so that, since the resistor **63** has precisely half the resistance of the resistor **39**, the current through the emitter-collector junction of the transistor **57** will be twice that of the current through the similar junction of the transistor **45.** If the voltage level at the junction of the resistors **39** and **43** shifts to a more negative value, for example, the input to the operational amplifier **51** will shift to a more negative value causing the output of the operational amplifier to shift to a more positive value so that the anode of the zener diode **59** will shift to a more positive voltage level to a sufficient degree to cancel out, through the feedback resistor **65**, the more negative input through the input resistor **53**.

The collector of the transistor **57**, which is the output of the −2I current source **17**, is connected through the current switch **19** to the capacitor **13**. The current switch **19** includes a pair of transistors **69** and **71**. The transistor **71** operates as the current switch between the −2I current source **17** and the capacitor **13**. The transistor pair **69** and **71** operate such that if the base of the transistor **71** is more positive than the base of the transistor **69**, the current switch will be on, that is, the collector emitter junction of the transistor **71** will be a low impedance connection between the −2I current source **17** and the capacitor **13**. Whenever the base of the transistor **69** is more positive than the base of the transistor **71**, the transistor **71** will be nonconductive and the current switch **19** will be off. The transistors **69** and **71** thus operate as a current mode pair. As is well known, when the transistor **71** is conductive, both the base and the emitter of the transistor **71** will become more positive so that the emitter of the transistor **69** becomes more positive than the base of the transistor **69**, causing the transistor **69** to become nonconductive. When, however, the base of the transistor **69** becomes more positive than this level, the transistor **69** will conduct current from a positive voltage source +V2 at a point **73**. Current will now flow between the positive voltage source at point **73** and the negative voltage source at point **61**, raising the potential at the emitter of the transistor **71** to reverse bias the transistor **71** to shut off the current switch **19**. A resistor **74** is connected between the base of the transistor **69** and ground and a resistor **75** connected between a point **77** which is connected to a negative voltage source −V3 and the base of the transistor **69** operate to bias the base of the transistor **69**. In the preferred embodiment, the resistors **74** and **75** are selected to bias the base of the transistor **69** at −250 millivolts. This bias level aids in the proper control of the current switch **19** from the digital driver **35** as will be explained below.

The voltage at the integrator or capacitor **13** is monitored through a line **79** by a common collector transistor amplifier **81** which serves as the buffer amplifier **23**. The transistor **81** has a collector connected to a positive voltage source +V2 at a point **83** and has a high input impedance and relatively low output impedance to isolate the capacitor **13** from the voltage-to-current converter **27** and from the output of the triangle wave generator on line **85**.

The voltage-to-current converter **27** comprises a pair of resistors **85** and **87** connected between the output of the buffer amplifier **23** and a negative voltage source −V3 at a point **89**; and a resistor **91** and capacitor **93** connected in series with another and in parallel with the resistor **85**.

The combination of the resistor **91** and capacitor **93** in the voltage-to-current converter operates as a lead network to alleviate any time delay which may occur between the voltage level at the integrating device **13** and the tunnel diode pair **29** and **31**, caused, for example, by the buffer amplifier **23**. This assures, therefore, that the tunnel diode pair will properly track the voltage level on the capacitor **13** so that threshold will be reached at precisely the proper voltage level.

The voltage-to-current converter **27** produces a current through the pair of tunnel diodes **29** and **31** which are connected between the junction of the capacitor **93** and the resistors **85** and **87** and ground. The voltage across the pair of tunnel diodes **29** and **31** is shown in FIG. 3*d* and may be compared with the voltage at the capacitor **13** shown in FIG. 3*a*. As will be noted, the current through the tunnel diodes **29** and **31** is in a direction from the voltage-to-current converter **27** to ground when the triangle waveform at the capacitor **13** is positive. Likewise, when the voltage at the capacitor **13** is negative, current will flow through the pair of tunnel diodes **29** and **31** from ground into the voltage-to-current converter **27**. As has been explained previously, when a tunnel diode is forward biased it will exhibit a relatively low impedance until a predetermined threshold current is reached, at which time the tunnel diode will immediately exhibit a relatively high impedance. Referring specifically to FIG. 3*d*, it will be noted that, in the preferred embodiment, the tunnel diode exhibits a first relatively low impedance between the time T1 and the time T2 as the triangle wave approaches the positive peak voltage level. At time T2, current through the forward biased tunnel diode **29** reaches the threshold level and the impedance of the tunnel diode **29** immediately increases so that, instead of exhibiting a voltage drop of approximately **100** millivolts, the tunnel diode **29** immediately exhibits a voltage drop of approximately 500 millivolts. As will be explained in more detail below, this transition of the tunnel diode **29** closes the current switch **19** so that a negative current −I is drawn from the capacitor **13** and the capacitor **13**, as shown in FIG. 3a, has a linearly decreasing voltage until time T3. Referring again to FIG. 3d, it will be noted that the tunnel diode **29** exhibits its relatively high voltage drop until the current therethrough reaches some positive value lower than the peak positive current value, at which time the tunnel diode **29** goes through a second transition to a relatively low voltage drop as shown at the time T4. The particular current level at which this second threshold occurs is relatively uncertain and, for this reason, a bracket **95** in FIG. 3*d* encloses a zone of relative uncertainty.

In a manner identical to that described above, when the capacitor **13** reaches a peak negative voltage at time **T3**, the current flowing in a forward biased direction through the tunnel diode **31** reaches the threshold level of this tunnel diode, so that the voltage drop across the tunnel diode **31** immediately increases to approximately 500 millivolts. This threshold causes, as will be explained below, the current switch **19** to turn off so that the positive current source **11** will increase the voltage of the capacitor **13**. This process continues as is shown in FIGS. 3*a* and 3*d*.

Referring once again to FIG. **2**, it will be noted that the digital driver **35** is likewise connected to the junction between the capacitor **93**, the resistor **85** and the resistor **87** and is thus tied directly to the anode of the tunnel diode **29**. The digital driver **35** operates as a latching device to maintain the current switch **19** in an on or off state after it has been triggered to one of these states by the pair of tunnel diodes **29** and **31**. A pair of transistors **97** and **99** operate as a current mode pair in a manner similar to the transistors **69** and **71**. The base of the transistor **97** is subjected to the voltage drop across the tunnel diode pair **29** and **31** shown in FIG. 3*d*. The base of the transistor **99** is connected to the base of the transistor **69** so that it is biased to a −250 millivolts unless a different signal is impressed on it, as will be explained below. The collectors of the transistors **97** and **99** are connected through resistors **101** and **103** to positive voltage supplies +V1 and +V2 at point **105** and point **107**, respectively. The emitters of the transistors **97** and **99** are connected through a common resistor **109** to a negative voltage supply −V3 at a point **111**. In addition, the emitter of an additional transistor **113** is connected to the junction of the collector of the transistor **97** and the resistor **101**. The base of the resistor **113** is connected to a positive voltage source +V2 at a point **115** and the collector of the transistor **113** is connected to the base of the transistor **99** and the base of the transistor **69**. A rectangular waveform, as shown in FIG. 3*b*, exists at the collector of the transistor **99** as an output rectangular waveform on a line **117**. The base of the transistor **99** and the base of the transistor **69** exhibit a voltage curve which is shown in FIG. 3c.

The operation of the digital driver **35** in latching the current switch **19** may now be described in reference to both FIG. 2 and FIG. 3. Beginning with time **T1**, assume that the current switch **19** is off, that is, the transistor **71** is nonconductive. Thus, only the positive current source **11** is connected to the integrating device **13** and the charge level on the integrating device **13** is increasing so that the voltage as shown in FIG. 3a is increasing as a linear function. During this voltage buildup period the base of the transistor **69** and the base of the transistor **99** are each maintained at a level of +250 millivolts by current flowing from the voltage source at point **105** through the resistor **101** and the transistor **113**. As will be recognized, when the transistor **97** is off, the transistor **113** is biased for conduction and current flowing through the transistor **113** from the voltage source at **105** will maintain the base of the transistors **69** and **99** at +250 millivolts as shown in FIG. 3*c*. Thus, each of the transistors **69** and **99** is biased for conduction while the transistors **71** and **97** are biased for nonconduction. This occurs because the bases of the transistors **69** and **99** are more positive than the bases of the transistors **71** and **97**. The bases of the latter transistors are connected to the pair of tunnel diodes **29** and **31** and have a voltage level as shown in FIG. 3*d*, that is, a voltage level which is more negative than the voltage level shown in FIG. 3*c*. The rectangular output waveform on line **117**, as shown in FIG. 3*b*, remains at a negative voltage level since the collector-to-emitter junction of the transistor **99** is conductive and permits the voltage on the line **117** to be influenced by the voltage supply at **111**.

When the tunnel diode **29** reaches its threshold current level, the voltage drop across the pair of tunnel diodes **29** and **31** immediately thresholds to an increase level as shown in FIG. 3d so that the voltage drop across the pair of tunnel diodes **29** and **31** is approximately 500 millivolts. Thus, the voltage at the base of the transistors **71** and **97** immediately follows this voltage increase so that, since the base of the transistors **69** and **99** is still maintained at a level of +250 millivolts, the bases of the transistors **71** and **97** are now more positive. The transistors **71** and **97** therefore immediately become conductive and the transistors **69** and **99** immediately become nonconductive. Current will now flow between the voltage source at point **105** through the transistor **97** to the voltage source at point **11**, drawing current from the transistor **113** so that the transistor **113** becomes reverse biased and is shut off. The voltage level on the base of the transistors **99** and **69** is now controlled by the bias resistors **73** and **75** and therefore maintained at a level of −250 millivolts. The output rectangular waveform on the line **117** now goes to a positive level since the transistor **99** is nonconductive and the voltage at the source **107** is impressed upon the line **117**.

It will be recognized by those skilled in the art that a certain time lapse occurs in the switching of the transistors **97** and **99** and the resulting change in the bias level on the base of the transistors **69** and **99**, due to the inherent time delays in the system components. However, the tunnel diode pair **29** and **31**, being directly connected to the base of the transistor **71**, will cause the transistor **71** to immediately become conductive without the interposition of a time delay. Therefore, the current switch **19** immediately becomes conductive and it is only necessary that the bases of the transistors **69** and **99** reach their new potential of −250 millivolts before the bases of the transistors **69** and **99** are reduced in potential to +250 millivolts. In other words, it is only necessary to assure that the bases of the transistors **69** and **99** remain more negative than the bases of the transistors **71** and **97**. As shown in FIG. 3*d*, the reduction in the voltage level at the bases of the transistors **71** and **97** occurs relatively slowly as the voltage-to-current converter tracks the output triangle waveform of FIG. 3*a*. The digital driver circuit **35** therefore operates as a latching device preparing the bases of the transistors **69** and **99** for the threshold of the tunnel diode **31** at the negative peak value of the triangle waveform.

When the triangle waveform on the line **85** shown in FIG. 3*a* reaches a negative peak value, the current from ground through the tunnel diode pair **29** and **31** into the voltage-to-current converter **27** reaches the threshold level of the tunnel diode **31**. Thus, at time T3 shown in FIG. 3d the voltage across the pair of tunnel diodes **29** and **31** thresholds to approximately 500 millivolts so that the bases of the transistors **71** and **97** immediately reach a value of approximately −500 millivolts. Since, as explained previously, the bases of the transistors **69** and **99** are still maintained at approximately −250 millivolts by the bias resistors **73** and **75**, the transistors **69** and **99** become conductive, their bases being more positive than the bases of the transistors **71** and **97**. The current switch **19** therefore becomes nonconductive since the transistor **71** is biased for nonconduction and current is supplied to the integrating device **13** solely by the positive current source **11**. The transistor **97** is nonconductive so that current will now flow to forward bias the transistor **113** to clamp the bases of the transistors **69** and **99** at a level of +250 millivolts. This +250 millivolts level is sufficient to assure that the bases of the transistors **69** and **99** remain more positive than the bases of the transistors **71** and **97** until the thresholding of the tunnel diode **29**, as was explained previously. Again, a certain time delay is inherent in the digital driver circuit **35** in driving the bases of the transistors **69** and **99** to the +250 millivolt level. However, this time is permissible since the tunnel diode **31** remains at its relatively high voltage drop level until the second threshold level of this tunnel diode is reached at time T5 of FIG. 3*d*, so that the time delay in the digital driver circuit **35** is masked by the direct coupling of the tunnel diode pair **29** and **31** to the current switch **19**.

What is claimed is:

1. A triangle wave generator capable of high frequency operation, comprising:
- a current source;
- an integrating device coupled to the output of said current source;
- a switch, interposed in series between said current source and said integrating device; and
- a tunnel diode, responsive to the voltage output of said integrating device, said tunnel diode being directly connected to said switch to directly drive said switch to close the circuit between said current source and said integrating device, without the interposition of a bistable device between said tunnel diode and said switch which would delay the operation of said switch in response to said tunnel diode.

2. A triangle wave generator as defined in claim **1** additionally comprising:
- a second tunnel diode, responsive to said voltage output of said integrating device, said tunnel diode being directly connected to said switch to directly drive said switch to open the circuit between said current source and said integrating device, without the interposition of a bistable device between said second tunnel diode and said switch which would delay the operation of said switch in response to said second tunnel diode.

3. A triangle wave generator as defined in claim **2** additionally comprising:
- a latching circuit, responsive to said pair of tunnel diodes for maintaining said switch in a closed or open configuration between successive driving of said switch by said tunnel diode and said second tunnel diode.

4. A triangle wave generator as defined in claim **1** additionally comprising:
- a second current source connected to said integrating device, said integrating device connected to integrate the sum of said current source and said second current source.

5. A triangle wave generator, comprising:
- means for generating a positive-going ramp signal;
- means for generating a negative-going ramp signal;
- switching means connected in series with one of said positive-going and negative-going ramp signal generating means for selectively producing said positivegoing ramp signal or said negative going ramp signal as an output signal;
- a tunnel diode, responsive to said output signal for producing a triggering signal; and
- means for directly connecting said tunnel diode to said switching means to directly drive said means for selectively producing with said triggering signal without the interposition of a bistable device between said tunnel diode and said switching means which would delay operation of said switching means in response to said triggering signal.

6. A triangle wave generator, as defined in claim **5**, additionally comprising:
- latching means for preventing a change in the operation of said selectively producing means in the absence of said triggering signal.

7. A triangle wave generator as defined in claim **6**, additionally comprising:
- a second tunnel diode responsive to said output signal for producing a second triggering signal; and
- means for connecting said second triggering signal to directly drive said switching means.

8. A waveform generator, comprising:
- a first current source for producing a first current **I**;
- a second current source for producing a second current **−2I**;
- a current switch connected to control current from said second current source;
- an integrating device connected to said first current source and series connected by said current switch to said second current source to alternately integrate the current from said first current source or the sum of the currents from said first and second current sources in accordance with the state of said current switch, said integrating device producing an output voltage signal;
- means for generating a control current signal proportional to said output voltage signal;
- a pair of tunnel diodes connected in reverse polarities to conduct said control current signal, said tunnel diodes producing a triggering signal at positive and negative predetermined threshold levels of said control current;
- means directly coupling said triggering signal to said current switch to control the state of said current switch without the interposition of a bistable device between said tunnel diode pair and said switch which would delay the operation of said switch in response to said tunnel diode pair; and
- a latching circuit coupled to said triggering signal and said current switch for maintaining said current switch in a predetermined state between successive triggering signals.

9. A waveform generator as defined in claim **8** wherein said current switch comprises a current mode transistor pair, one of said transistors connected to selectively conduct current from said second current source to said integrating device.

10. A waveform generator as defined in claim **9** wherein the other of said transistors is controlled by said latching circuit and said one of said transistors is directly coupled to said pair of tunnel diodes.

11. A waveform generator as defined in claim **8** wherein said control current signal generating means comprises a lead network for eliminating time delays between said output voltage signal and said tunnel diode pair.

12. A waveform generator as defined in claim **8** additionally comprising:

means for controlling said second current source in response to said first current I to maintain a predetermined relationship between said first and second currents.

13. Apparatus for producing an output signal having alternate positive-going and negative-going ramp signal portions, comprising:

integrating means;

a current source;

a switch series connected between said integrating means and said current source to control the current flow between said current source and said integrating means; and

a tunnel diode responsively connected to said output signal and connected directly to said switch to directly drive said switch periodically without the interposition of a bistable device between said tunnel diode and said switch which would delay operation of said switch in response to said tunnel diode.

14. Apparatus for producing an output signal as defined in claim **13** additionally comprising:

a second current source connected to continuously supply current to said integrating device.

15. Apparatus for producing an output signal as defined in claim **13** additionally comprising:

means responsive to said tunnel diode and connected to said switch for maintaining the state of said switch constant between periodic driving of said switch by said tunnel diode.

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