

magnetic salts. A bucking coil was used, and the resistive divider and ratio transformer were interchanged. A 1000:1 fixed resistive divider was placed across the output of the adjustable  $S$  divider since  $S$  was quite small; this fixed divider also presented a low impedance to the bridge secondary circuit and permitted a 100:1 stepup transformer to be used at the detector amplifier input to in-

crease sensitivity. For the metal samples,  $S'$  was measured as a function of  $(f)^2$  and extrapolated to zero frequency to correct for small eddy current effects.

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## 500 MHz Ring Counter

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This paper describes a new tunnel diode-transistor ring counter employing current mode operation. With suitably shaped input pulses it is capable of operating reliably at input repetition rates in excess of 500 MHz.

### INTRODUCTION

A RING counter is essentially a number of flipflops connected in a ring and driven from a common input, with coupling arranged to prime and reset adjacent flipflops. Initially one flipflop is in a state different from the rest and successive input pulses propagate this state around the ring. A ring counter made up of  $n$  flipflops thus has a scaling capacity of  $n$ .

A ring counter employing tunnel diodes as the basic flipflops is described in this paper. Coupling between them is by means of transistor current switches which perform the functions of priming and resetting. The maximum speed of operation depends essentially on the delay in priming the next tunnel diode.

### PRINCIPLE OF OPERATION

Figure 1 shows the basic arrangement of a quinary ring counter. Each tunnel diode is biased by a constant current  $I_b$  and can be in either a 0 or 1 state, as shown on the static characteristic diagram of Fig. 2. Switches  $S_1$  to  $S_5$  are controlled by tunnel diodes TD1 to TD5 respectively. Each switch is normally open but closes when the associated tunnel diode switches to a 1 state.

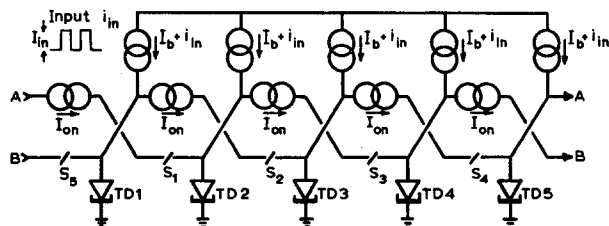


FIG. 1. Basic arrangement of ring counter.

Initially one of the tunnel diodes (say TD5) is switched into a 1 state.<sup>1</sup> Switch  $S_5$  is therefore closed and current  $I_{on}$  is extracted from TD4 and supplied to TD1. With reference to Fig. 2, TD4 is in a  $0_n$  state and TD1 is in a  $0_p$  state, i.e., it is primed. Input current pulses of amplitude  $I_{in}$ , where  $I_p - I_b - I_{on} < I_{in} < I_p - I_b$ , are applied simultaneously to all the tunnel diodes. The first pulse switches TD1 to a 1 state and closes switch  $S_1$ . TD5 is reset to a  $0_n$  state and TD2 becomes primed, i.e., in a  $0_p$  state. Following the reverse switching of TD5 switch  $S_5$  opens and TD4 returns to a  $0_b$  state. The 1 state and its adjacent  $0_n$  and  $0_p$  states have been thereby shifted one stage around the ring. Further pulses will propagate these states around the ring one stage at a time.

Figure 3 shows the theoretical waveforms of the tunnel diodes in response to a number of successive input pulses.

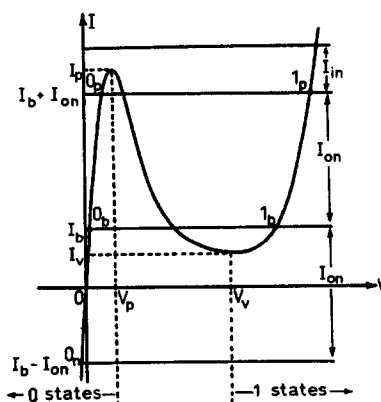


FIG. 2. Static characteristic diagram showing 0 and 1 states.

<sup>1</sup> A current of magnitude greater than  $(I_p - I_b)$  supplied momentarily to this tunnel diode will achieve this.

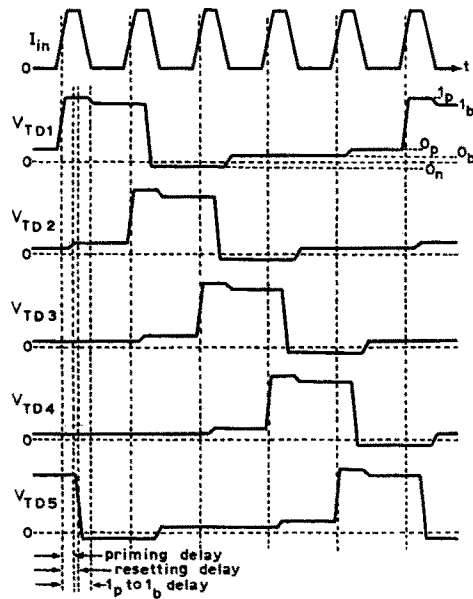


FIG. 3. Theoretical waveforms illustrating the operation of the counter.

The delays indicated are self explanatory. The output can be taken from any of the tunnel diodes.

It is worth noting that since three different states are propagated around the ring, the minimum number of stages is three. Such a counter will operate at a much reduced maximum speed because of additional delays in the priming of a following stage, which is initially in a  $0_n$  state.

### ACTUAL CIRCUIT OF COUNTER

The practical arrangement of the ring counter is shown in Fig. 4. A long-tailed pair is employed as the current switch. Zener diodes passing a minimum current  $I_z$  are used to maintain the necessary collector-emitter potential differences. The maximum current in the Zener diodes is  $I_{on} + I_z$  where  $I_{on}$  is the collector turn-on current. The constant reverse current  $I_r$  from each of the tunnel diodes helps to define  $I_b$  which is equal to  $I_{on} + 2I_z - I_r$ .

The actual values of  $I_b$  and  $I_{on}$  depend on the  $I_p$  and  $I_v$  of the tunnel diodes used. For RCA 1N3858 Ge tunnel diodes with  $I_{pmin}$  of 9.5 mA and  $I_{vmax}$  of 1.2 mA,  $I_b$  and  $I_b + I_{on}$  were selected to be respectively 0.5 mA above  $I_{vmax}$  and 0.5 mA below  $I_{pmin}$ .

The negative line associated with  $I_r$  is a good point from which to drive the counter. By using a Zener diode, the input voltage  $V_{in}$  across the 50  $\Omega$  cable terminating resistor is coupled to this line, thus effectively transforming  $V_{in}$  into input currents. This method of driving the counter also eliminates the problem of isolation of the tunnel diode inputs.

The counter was constructed on a single sided circuit board using the copper laminate as an earth-plane. Particular

attention was paid to the circuit layout and all the leads in the forward switching path of the counter were kept as short as physically possible. Figure 5 is a photograph of the counter.

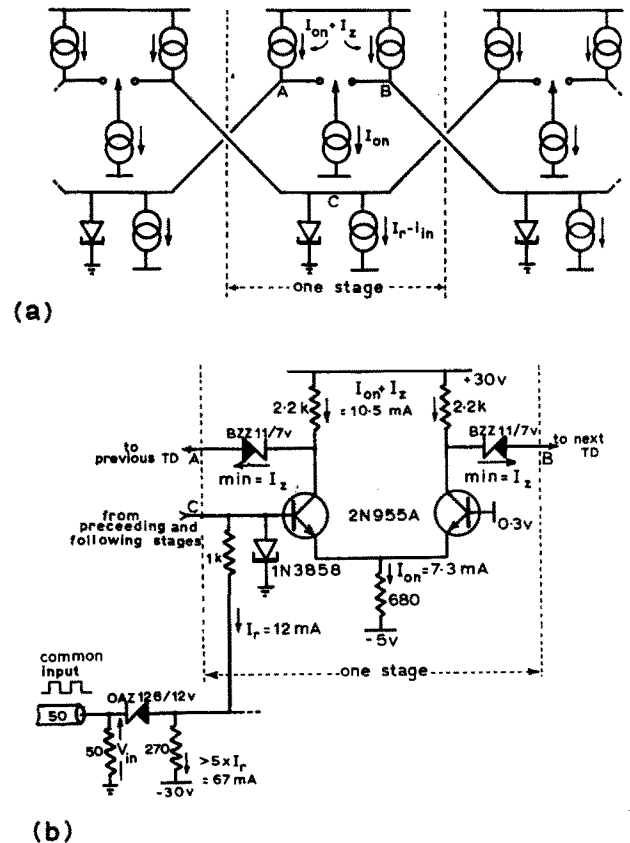


FIG. 4. Practical arrangement of ring counter. (a) Schematic arrangement of three adjacent stages. (b) Actual circuit of single stage.

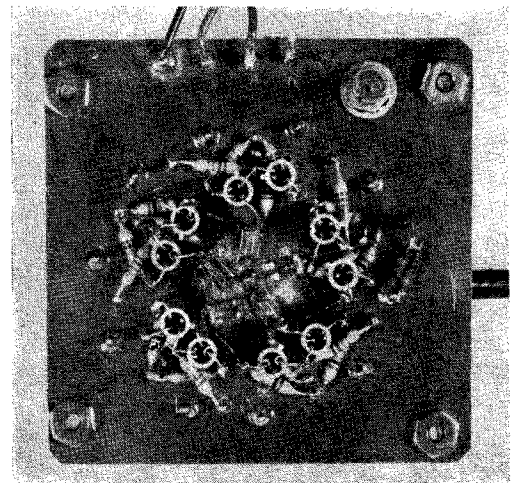


FIG. 5. Photograph of quinary ring counter.

<sup>2</sup> Motorola Switching Transistor Handbook (1963), 2nd ed., pp. 254-261.

### MAXIMUM SPEED OF OPERATION

Theoretically the counter should be able to operate reliably at very high input repetition rates. The maximum rate depends on the speed with which the next tunnel diode can be primed. An expression for the turn-on time<sup>2</sup> of the priming current, *viz*,

$$t_{on} = [I_{on}(1/\omega_T + R_L C_{ob})] / [\Delta E / (R_{in} + 2r_B')]$$

gives an approximate figure of 1.5 nsec on substitution of the following typical values for a 2N955A transistor<sup>3</sup>:

$f_T$ = current gain-bandwidth product	= 1000 MHz
$C_{ob}$ = output capacitance (common base)	= 4 pF
$r_B'$ = base spreading resistance	= 100 ohm
$I_{on}$ = collector turn-on current	= 7.5 mA
$R_L = R_{in}$ = tunnel diode resistance	= 10 ohm
$\Delta E$ = maximum potential difference between the bases of long-tailed pair	= 0.2 volt.

If the rise time of  $\Delta E$  ( $\sim 0.2$  nsec) and additional extraneous delays ( $\sim 0.1$  nsec) are taken into account the modified figure of 1.8 nsec corresponds to a maximum operating frequency of about 550 MHz. The predicted and experimental limiting frequencies are in quite good agreement.

Figure 6 shows waveforms of the counter in operation. When a constant current  $I_{in}$  is supplied to the input, the counter multivibrates at a frequency  $\frac{1}{5}$  of the maximum. This is shown in Fig. 6(a) where the waveforms are those observed across two adjacent tunnel diodes. They indicate that the counter can operate at a maximum frequency of about 500 MHz. Furthermore, for proper operation as a counter, the width of the input pulse must be less than  $1/f_{max}$ . Figures 6(b) and 6(c) show the counter operating at 500 MHz and 250 MHz, respectively.

The maximum frequency quoted above is not the ultimate maximum of the counter. Currently available transistors should be able to boost the counter's maximum frequency to about 1 GHz. No attempt has been made to improve the maximum frequency as the problem of shaping the input pulses to conform to the width requirement demands more urgent attention.

### GENERAL COMMENTS

The following are a few of the outstanding features of the counter. It is simple, reliable, and capable of operating at very high repetition rates. In addition, being a current mode counter it has the advantages of high dc stability,

<sup>3</sup> Although production of this transistor type has now been discontinued by its manufacturer (RCA), any fast switching npn transistor can be substituted in its place since the current switching property of the long-tailed pair circuit is relatively insensitive to transistor characteristics as long as similar transistors are used within a pair. The speed performance limits will depend to some extent on the parameters of the substituted transistor.

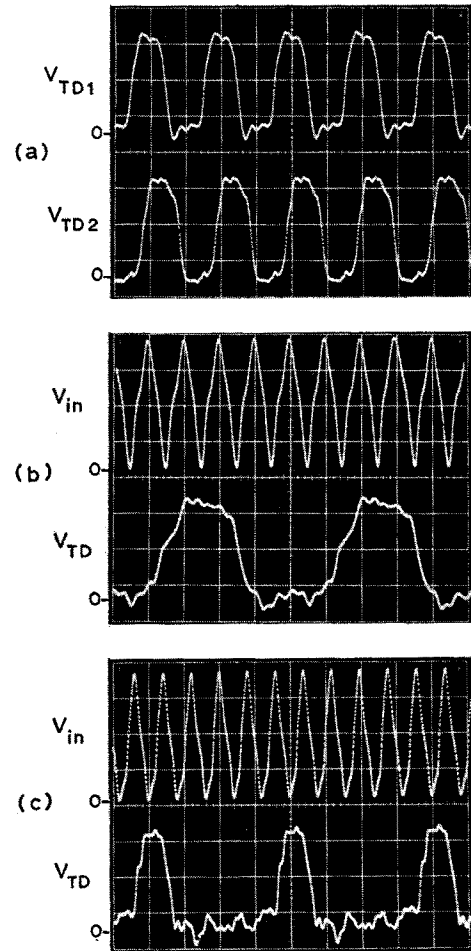


FIG. 6. Waveforms of the counter. (a) Multivibrator operation with constant  $I_{in}$ , (vert—0.2 V/div; hor—5 nsec/div). (b) Operation at 500 MHz, (vert—top 1 V/div, bottom 0.2 V/div; hor—2 nsec/div). (c) Operation at 250 MHz, (vert—top 1 V/div, bottom 0.2 V/div; hor—5 nsec/div).

good noise immunity, and only slight dependence on many of the semiconductor parameters.

A major disadvantage is that, in common with most ring counters, it requires input pulse shaping and the input pulse must be capable of driving five circuits in parallel. In particular, the width must be less than  $1/f_{max}$ . The problem of producing narrow pulses over a wide range of repetition rates is by no means easy to solve and investigations are proceeding. The necessary condition that one of the tunnel diodes be initially in a 1 state is only a minor disadvantage.

### ACKNOWLEDGMENTS

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