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B. H. Candy

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Photon counting circuits

B. H. Candy

Physics Department, University of Adelaide, South Australia 5001, Australia

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Two photon counters with variable dead times are described, one of simple design which is suited for low count rates and the other for system dead times down to 2 ns. Cheap, well-known components are used and the counters were designed by computer aid with a criterion that circuit performance be relatively insensitive to component values. An example of PCB layout is presented.

INTRODUCTION

Two photon counters are described which were designed for different counting regimes: one for low level light detection which was built for a UV monochromator,[1] the other for short dead-time applications which is to be used in a lidar system of the Mawson Institute within the Adelaide Universities' atmospheric research program.[2] An accompanying review paper discusses photomultiplier characteristics relevant to photon counting.[3]

I. THE SLOW PHOTON COUNTER

A simple photon counter with a dead time adjustable down to a few tens of nanoseconds is shown in Fig. 1. The low noise preamplifier in Fig. 1(a) takes advantage of the high output impedance of photomultipliers (PM). This amplifier should be connected directly to the PM base (with leads of less than a few centimeters) and housed within the base screening. If this is not possible, the preamplifier of the "fast" photon counter shown in Fig. 4 should be implemented, which also has provision for measuring the mean anode current. In excessively noisy rf environments it may be advantageous to operate the system without a preamplifier.

The first stage used in Figs. 1(b) and 4(a) has an input impedance of 50 Ω and is worthy of comment. The input impedance of a small signal microwave transistor in the common emitter configuration, with a 50-Ω collector load, is typically a few hundred ohms resistive at low frequencies and $\sim$50-Ω resistive (usually less) at a particular UHF frequency. The impedance versus frequency roughly follows a semicircle joining these two points on a Smith chart. S_{21} is large and real at low frequencies ($\sim$25 at 180° for $I_c \sim 10$ mA) and decreases to a fraction of this value at UHF frequencies, with an associated phase angle of between 0° and 90°. Consequently, the inductive component resulting from the feedback resistor in these stages tends to cancel with the capacitive part of S_{11} and the corresponding resistive components move in opposite directions with frequency. A BFR90A has the property that this cancellation is near perfect and the VSWR of the stage is small ($<$1.2:1, typically 1.1:1, to 500 MHz). One way of adjusting the collector currents so as to set the input impedance to 50 Ω is to calibrate a source with a 50-Ω resistor and then compare levels when the source is connected to the amplifier. A 10-MHz source fed through a 1-kΩ resistor is satisfactory. The level at the input should not exceed 30 mV in order to avoid overload conditions. A directional coupler, VSWR meter, or network analyzer are obviously suitable instruments for this adjustment but are not common laboratory instruments.

Photon counters consisting of purely direct coupled stages have dc drift problems if tubes are run at low gains (see Ref. 3). Also if the system is run with the discriminator set to pass $>90\%$ of single-photon pulses, most overlapping pulse events will be seen as a single event. Thus, at high count rates pile-up effects are pronounced. If ac coupling is used with long time constants then the discriminator threshold effectively wanders owing to the unipolar nature of photomultiplier pulses. To avoid these problems, this circuit contains an "RC differentiator" stage.

An ECL line receiver proved to be the most satisfactory limiting amplifier which is readily available and cheap. A 74F00 cannot be implemented for this purpose because it is unstable. The dc feedback is wired about the first limiting stage and discriminator action is set by a variable offset. The choice of an ECL dividing stage is not a result of speed considerations but for convenience in implementing a delay using one of the line receivers. No attempt has been made to optimize group delay. Nevertheless observed responses seem satisfactory as shown in Fig. 2.

Photon counting performance can be assessed by measuring the time statistics of detected pulses. This is discussed in Ref. 3, where it is recommended that a function of

$$f(n) = \frac{(n+1)P(n+1, T)}{P(n, T)}$$

should be plotted for a Poissonian source. For a nonparalyzible system the plot should yield a straight line of slope $-2\bar{n}\tau$ (Ref. 4) if $T \gg \tau$. Here $P(n, T)$ is the probability of detecting n counts in a period T, $\bar{n}$ is the observed mean number of counts in Hz, and τ is the system dead time. If the statistics of the detected light is to be determined by means of $f(n)$, then it is cheapest to translate to TTL levels first before the flip–flop stages as shown in Figs. 1(c) and 3.

Meaningful measurements of light statistics require that either the mean delay between counts is much greater than the system dead time so that a plot of $f(n)$ does not reflect the system dead time, or alternatively, that the dead time be constant. The latter criterion is not met with the "RC" dead time switched in because the double-pulse dead time is different from that of multiple or cw pulses. This is true also for the "RC" differentiator stage unless the product, RC, is much less than the full width at half-maximum

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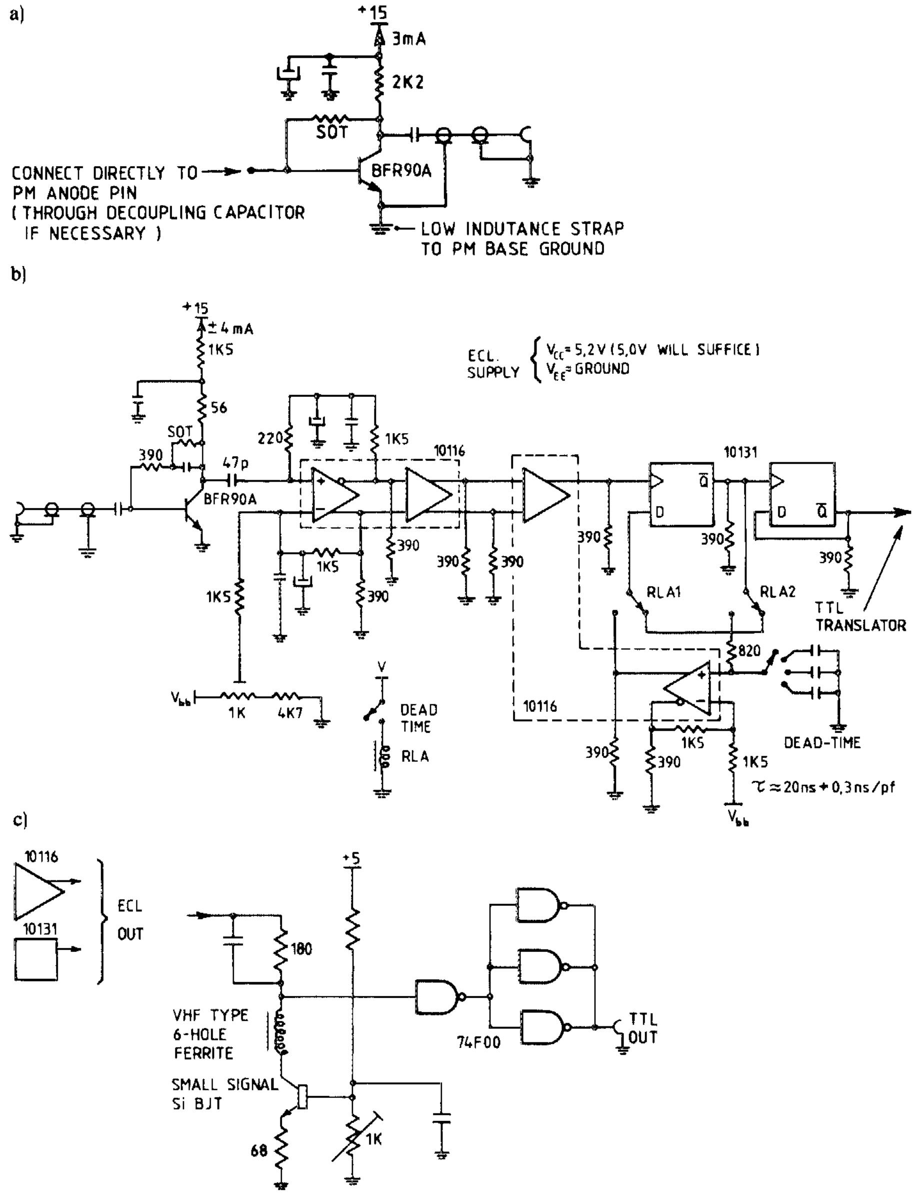

FIG. 1. Slow photon counter. (a) High impedance preamplifier, (b) differentiator, limiter, and prescaler stages, (c) ECL to TTL translator. "SOT" stands for "select on test."

of anode pulses. However, this is unsatisfactory in terms of signal attenuation and enhanced sensitivity to PM pulse or electronic ringing. Thus, a compromise should be made. If dead time is an important parameter, then the fast photon counter described in the next section should be considered.

Care should be taken with the layout of this system which should be constructed according to the principles described in the next two sections. All unmarked capacitors are 0.1-μF subminiature monolithic ceramics ($<5\times5$ mm). Low powered Schottky may be substituted for the control IC's in Fig. 3 (except for the 74F00). However, if these are used throughout the circuit may not operate successfully because of excessive propagation delays.

II. THE FAST PHOTON COUNTER

Circuits for a photon counter with a short dead time are shown in Fig. 4 and its basic electronic characteristics are listed in Table I.

The circuits in Refs. 5–14 and those listed in Ref. 14 were inspected as possible candidates in various arrangements for a fast photon counter. However, these were considered unsatisfactory for a number of reasons, e.g., poor

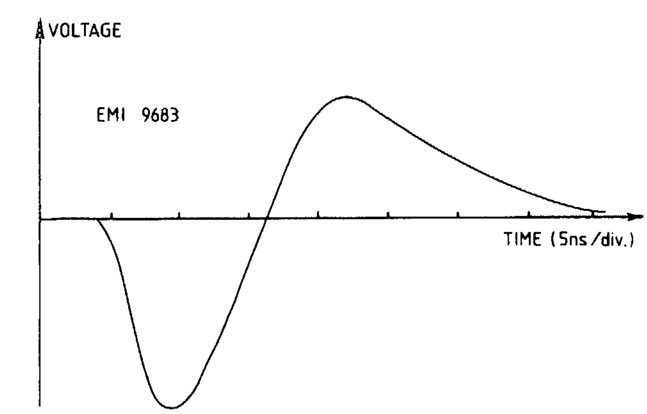

FIG. 2. Voltage waveform of an EMI 9683 at the output of the first 10116 stage.

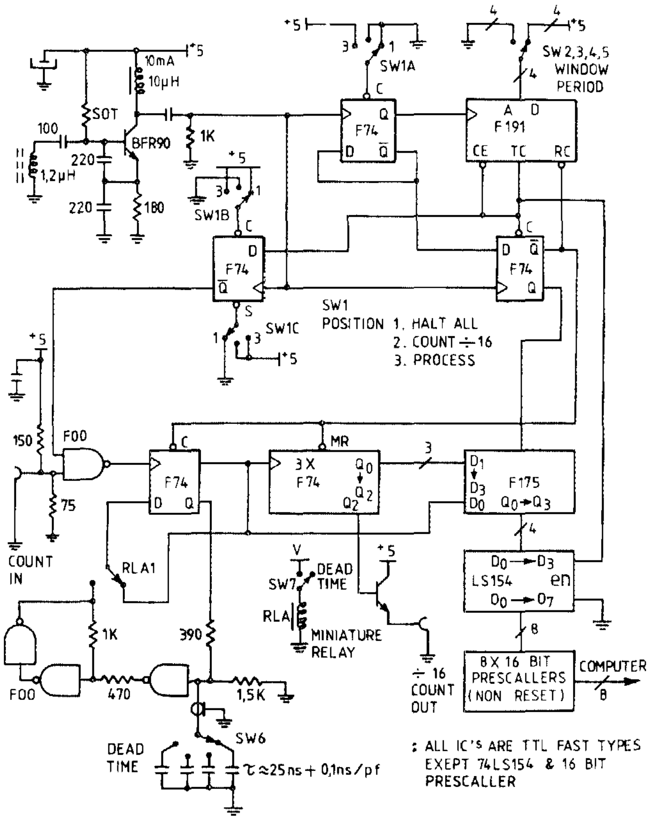

FIG. 3. Circuit for determining counting statistics.

VSWR, group delay, noise figure, or stability under a variety of load conditions.

The choice of the circuits presented here were conceived on intuitive grounds. Most stages have good isolation and each transistor sees a predominantly mid-valued resistance at either input or output. These critiera are conducive to good stability. A flat frequency response to high frequencies is achieved through the use of "peaking" inductors and capacitors, the values of which are not critical. In most cases the inductors are resistor leads wound into a spiral. Delay lines are used for both "differentiation" and dead time.

Many of these stages could have been implemented using microwave IC's. However, these are either expensive or (the cheaper ones) do not have a satisfactory performance. If integrated circuits are used, the easiest way to achieve "differentiation" is by means of the setup shown in Fig. 5. Alternatively, a 25-Ω shorted delay line (two 50-Ω lines in parallel) may be connected to any 25-Ω junction in the linear stages: for example, to the line connecting the preamplifier (50-Ω output impedance) and the following stage (50-Ω input impedance). The total length of line connecting these two stages must be kept much shorter than the delay line length. Fast ECL line receivers such as the 100116 cannot be successfully used as limited amplifiers owing to excessive crosstalk between amplifiers and hence instability. In any case, their frequency response is unsatisfactory. The semiconductors were chosen on grounds of availability and price.

A computer was used for design optimization. The circuits were analyzed by standard two-port linear parameters. Some circuits[10,12,14] require algebraic analysis unless three-port parameters are used. The S parameters of a range of passive components and transistors were measured. Simple lumped models were derived from the former results and data of the transistors with the highest and lowest MAG at 500 MHz were used in the optimization. In fact, there was little difference between samples of devices of the same type available to the author. Table II lists the effective inductive component of various 100-Ω resistors which were soldered to a test jig practically leadless. The simple passive models proved insufficient at microwave frequencies where stability is critical. As a "rule of thumb" instabilities typically occur between 1.5 and 2.5 GHz for BFR90A's and MRF901's, 2 and 4 GHz for NE645's and HXTR3101's, and 2 and 10 GHz for GaAs FET's in these types of design of wideband circuits. Thus, the computer results served as a guide to possible instabilities and these were checked empirically if a circuit appeared attractive at lower frequencies. The computer analysis agreed well with measured results up to ~ 1 GHz. Table III is a flow chart for the optimization routine.

Performance criteria were chosen on both empirical grounds and a series of test trials on the computer. These had to be set carefully to avoid too large a computer printout. "Middle of the road" values were chosen for the final circuit values which were then assumed to be appropriately uncritical. The performance of the limiting circuits was checked for different degrees of limiting, i.e., different values of collector current about a chosen quiescent.

An example of PCB layout (the preamplifier) is given in Fig. 6. All lead lengths should be kept as short as possible and resistors with series inductance of < 3 nH should preferably be used (see Table II). All capacitors are chip types $\sim 0.1\ \mu$F, Tantalums $\pm 10\ \mu$F, diodes small signal silicon devices, and inductors 6-hole UHF-type ferrites unless otherwise stated. Small valued capacitors are miniature ceramics (with self-resonances in the UHF band). Care should be taken in soldering chip capacitors as these are fragile and only silver-loaded solder should be used in accordance with manufacturers' recommendations. Table IV lists the various inductor dimensions. The top ground planes should be connected completely about the PCB periphery to the bottom planes. BNC or N clamp or crimp sockets should be used rather than tag types unless these are connected as indicated in Fig. 7. All interstage coaxial cables should be short (< 3 cm) and these as well as supply lines are best rf decoupled with ferrite sleeves. If slow tubes are to be used, inductors $\sim 100\ \mu$H should be connected in series with the 6-hole ferrites.

A system using NE645 and HXTR3101 transistors has been constructed with an instrumental dead time of a little over 1 ns, which is similar to the circuits in Fig. 4 but with different passive values and additional components for stability. Figure 8 is an example of this system: the preamplifier, which has a noise figure of typically 2.7 dB. The input return of this circuit is < -20 dB and the gain 13.5 ± 0.5 dB to 1 GHz. Chip capacitors and resistors were implemented for this performance. SMA or N sockets and PTFE board proved more satisfactory than BNC sockets and fiberglass PCB, although the above characteristics were still met with

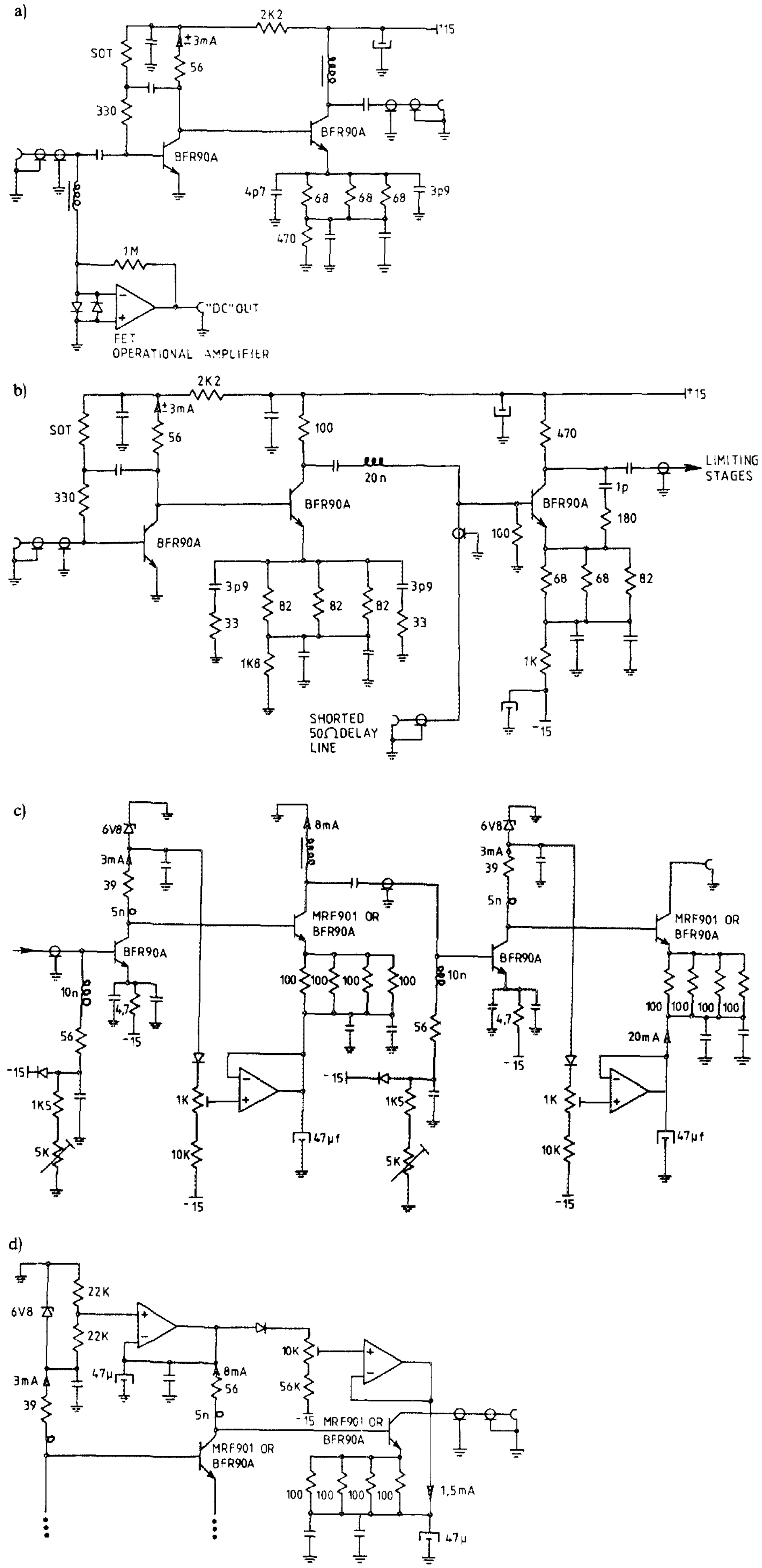

FIG. 4. Fast photon counter. (a) Preamplifier, (b) differentiator stage, (c) limiter stage with normally low output, (d) additional stage to (c) with normally high output.

TABLE I. Electrical performance of the fast photon counter to 500 MHz.

Characteristic	Preamplifier	Delay line differentiator and limiter
Noise figure (dB)	< 3.5, typ 3.2	<3.5, typ 3.2
Input reflection coefficient (S_{11} in dB)	< − 20	< − 20 typ − 23 at signal input < − 20 typ − 22 at delay input
Gain (dB)	20.0 ± 0.5	48 ± 1.5 with delay input open circuit
1-dB compression power at output (dB m)	11	16

TABLE II. Effective series inductance of various 100-Ω resistors.

Resistor type	Effective series inductance (nH)
Philips CR25	5
Philips CR16	2
Roederstein carbon composition 1/10 W	0.7
Roederstein MK1	<0.5
Roederstein MK2	3
Thick film 2×2-mm chip	<0.5

this latter technology. It is desirable to use a network analyzer to align various sections and to check on microwave stability. However, it is better to use microwave IC's for very short dead times which have an advantage of much smaller stray inductance than discrete circuits. These should be chosen on merits of VSWR and group delay. Prescalers such as a MC1699 operate to 1 GHz and have both enable and clear inputs.

In Sec. III D *1* of an accompanying paper,[3] a means of combating the effects of ringing in anode pulses is suggested. An easy way of implementing this is by modifying the last stage of the preamplifier to that shown in Fig. 9(a). If the ratio of the peak anode current intrinsic to the undulation in the tail of the main pulse to that of the peak in the main pulse, is u, then the resistors in Fig. 9(a) should be set to

$$R_2 = \frac{50[\sqrt{u(2-u)} - u]}{2u}$$

and

$$R_1 = \frac{50(R_2 + 50)}{R_2}.$$

VSWR is the most critical parameter to optimize so as to minimize reflections at both the preamplifier and delay line inputs. One way of reducing reflections between the photomultiplier and preamplifier is to make the photomultiplier "look" like 50 Ω. This can be achieved in most cases by connecting a 50-Ω resistor in series with an inductance from the anode pin to ground, via a decoupling capacitor if necessary, within the photomultiplier base housing. This procedure roughly halves the system gain and increases the system noise figure. A better alternative is to house the preamplifier within the photomultiplier base screening which has the added advantage of greater insensitivity to RFI. If the line connecting the photomultiplier together with the preamplifier to the rest of the system need be relatively long, it is best to use the circuit of Fig. 9(b). Here the resistor values are

$$R_1 = \frac{50(1 + u + 2\sqrt{u})}{1-u}$$

and

$$R_2 = \frac{5000R_1}{R_1^2 - 2500}.$$

For tubes with no undulations in the tails of their anode pulses, just the resistor R_1 in the collector circuit is necessary, which should be 50 Ω. The limiting amplifiers behave well under hard limiting conditions. For 23-dB compression the difference between the degree of "dc" compression to that at 500 MHz is only 3 dB.

The photon counting performance of this system was determined by measuring the counting statistics by means of a circuit similar to that of Fig. 3. Results for two tubes with a 2-ns differential delay line connected are given in Fig. 10. Small correlations are caused by three mechanisms. First, the dead time of all flip–flops for double pulses is slightly longer than that for multipulses. Second, the frequency spectral components are 20 dB below peak at 250 MHz for the 9814 and at 300 MHz for the 9683 at the EHT set for the measurements of Fig. 10. Thus, the high-frequency components of pulses are considerably enhanced. These are more likely to show signs of ringing than low-frequency components. Third, the main contributor; some pulses appear as double-overlapping events (see Sec. III D*1* in Ref. 3). These results show that the photon counter is well behaved; that is, it does not suffer from ringing or paralyzible dead-time effects.

An 11C70 or MC1670 is a suitable flip–flop for the first divider which requires a normally high clock input to avoid the enable input acting as a clock. To satisfy this requirement the stage shown in Fig. 4(d) needs to implemented (this is only necessary if the statistics are to be measured). 100131, 10H131 are suitable for the subsequent divider. Dead time can be achieved by means of a data delay between $\bar{Q}$ and D of the first flip–flop such as that shown in Figs. 1(b), 3, or 11. Unlike the "RC" delay, a cable is suitable for statistical measurements and a differential delay line is much more satisfactory in this respect as well. It is best to set the system dead time within a few percent of the reciprocal of the maximum expected count rate if possible, but without compromising accuracy. This procedure guards against the three mechanisms which lead to correlations described above as well as

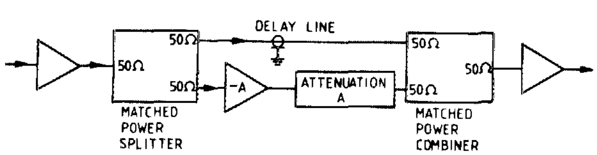

FIG. 5. Differentiation stage using wideband IC's.

TABLE III. Flow chart of a program used to assess satisfactory component values.

ENTER 1. ACTIVE DEVICE *S*-PARAMETER FILES (DIFFERENT DEVICES AND QUIESCENT CURRENTS)
2. STRAY INDUCTANCE AND CAPACITANCE VALUES
3. RANGE OF PASSIVE COMPONENT VALUES AND INCREMENTS
4. PERFORMANCE CONSTRAINTS

"DC" GAIN HIGH ENOUGH ? — NO → NEXT SET OF COMPONENT VALUES OR FILE

YES ↓

CHECK MICROWAVE STABILITY — SEVERE → NEXT SET OF COMPONENT VALUES OR FILE

MILD OR NONE ↓

CHECK PERFORMANCE (VSWR, GAIN etc OVER BANDWIDTH) — NOT OK → NEXT SET OF COMPONENT VALUES OR FILE

OK ↓

PRINT 1. "WORST CASE" CHARACTERISTICS
2. COMPONENT VALUES
3. NAME OF *S*-PARAMETER FILE
→ NEXT SET OF COMPONENT VALUES OR FILE

ion or luminescent afterpulses if these are significant and fall within the dead time. The period of the differentiator delay line should ideally be a little longer than the full width at half-maximum of the anode pulse (e.g., double) but needs to be shorter than this for most tubes if the dead time is to be set to a few nanoseconds. Dead times of about 2 ns should be achievable if very fast tubes such as a microchannel plate or a RCA-C31024 are connected to the system. It should be noted, though, that microchannel plates start to show signs of saturation at count rates ~ 1 MHz.[15,16] For steady light conditions, a spectrum analyzer display of a photomultiplier signal is that purely of the anode pulse Fourier components by virtue of the random arrival time of these pulses. This is a useful measurement for determining the speed of a tube if a fast oscilloscope is not available.

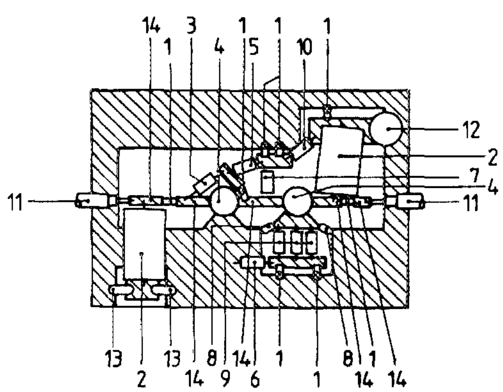

FIG. 6. PCB layout of the fast preamplifier. The indicated components are (1) chip capacitor > 10 nf, (2) 6-hole UHF-type ferrite, (3) 330-Ω resistor, (4) BFR90A, (5), bias resistor, (6) 470-Ω resistor, (7) 56-Ω resistor, (8) 3.9-pF capacitor, (9) 3×68-Ω resistors, (10) 2.2-$k\Omega$ resistor, (11) coaxial cable with screen soldered to ground plane, (12) tantalum capacitor, (13) small signal silicon diodes, (14) 50-Ω microstrip.

All power supplies should not be switched "on" to the circuits instantaneously (by means of a switch following the regulators plus storage capacitors). Rather, this process should take many milliseconds to avoid current surges in the semiconductors. This requirement is necessary also for the PM EHT if the cathode is grounded.

III. SOME FURTHER COMMENTS ON WIDEBAND PULSE TECHNIQUES

The protocol adopted for the design of the fast photon counter is time consuming and the author suggests that a quicker approach is to design empirically using a network analyzer. A wideband signal source and directional coupler together with an oscilloscope or gain-phase meter (HF to $\geqslant 1$ GHz) will suffice. "Three-dimensional" circuits can be built on a single-sided PCB where the copper is used as a ground plane. All lead lengths must be kept as short as possible (< 3 mm) and solder should be liberally spread on any low impedance joint so as to minimize inductance. Only low inductance capacitors such as chips or subminiature monolithic types should be implemented throughout and all supply points should be well decoupled to ground. These "3-D" circuits are reasonably mechanically stable especially if dc sections are also connected to the earth plane by means of capacitors. It is best to use subminiature PTFE coaxial cable

TABLE IV. Dimensions of inductors in Fig. 4.

Inductance (nH)	Number of turns	Mean diameter (mm)	Length (mm)
5	$1\frac{1}{2}$	2	2
10	$1\frac{1}{2}$	3.5	2
20	3	3.5	3.5

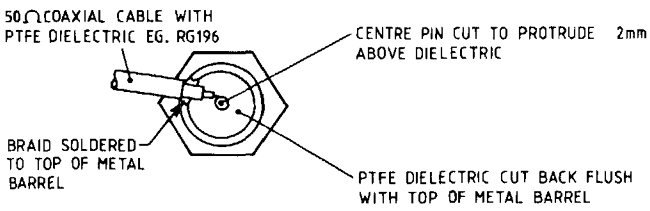

FIG. 7. Low inductance to a tag BNC connector.

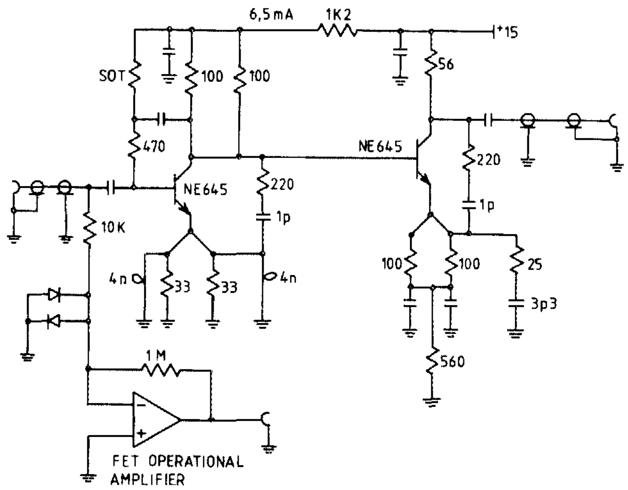

FIG. 8. Very fast low noise preamplifier.

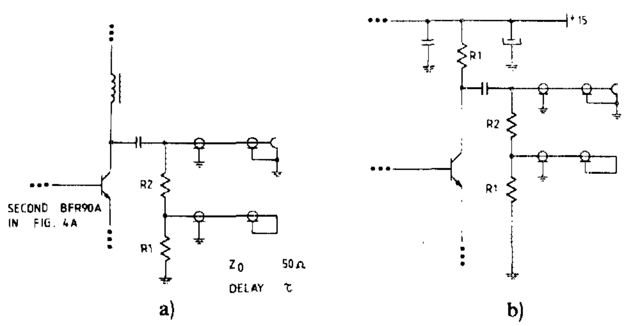

FIG. 9. Circuits for combating the effects of ringing in anode pulses: (a) may be used when the cable connecting the preamplifier to the next stage is short, while (b) should be implemented if this cable is long.

because the screen can be soldered directly to ground without damage to the dielectric (see Figs. 6 and 7).

If the detector instruments do not respond to several GHz, it is possible to detect microwave oscillations by three methods:

(1) By means of a biased low capacitance microwave detector diode fed into a high resistive load (≫50 Ω).

(2) If a cw source is fed into the input and the level is turned up so that mild overload conditions occur, intermodulation products of the signal harmonics with the oscillation can be seen on a spectrum analyzer.

(3) If fingers are placed near various stages at which or through which the oscillation is occurring, the system gain varies depending upon the interaction owing to the consequent varying limiting conditions. This technique can also be used to induce oscillations in circuits that are just stable.

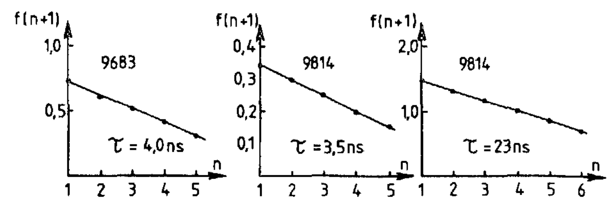

FIG. 10. Photon counting performance of the fast photon counter for two linear focused tubes. The "logic" dead time of (a) and (b) is purely that of the flip-flop while in (c) a delay time of ~20 ns is switched in.

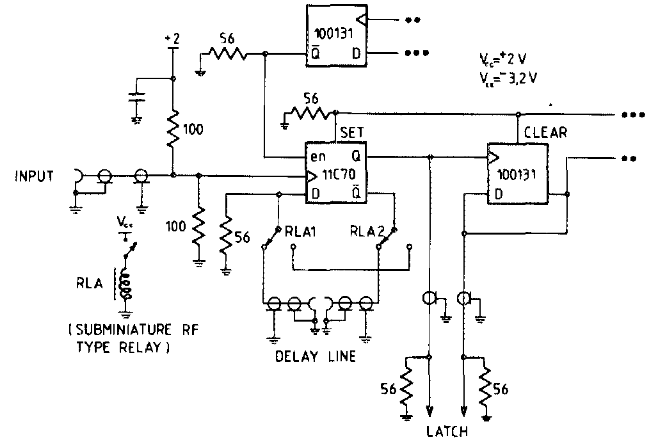

FIG. 11. Part of a high-speed counting analysis circuit similar to the slower version shown in Fig. 3.

It is best to carry out the gain tests in (3) at low frequencies, e.g., 1 MHz, as the impedance of fingers to 1 MHz is much greater than that "seen" by microwaves. Gain changes may be very small for mild instabilities and thus it is best to set the instrument scale to high sensitivity, e.g., "2 dB per division" on an analyzer.

ACKNOWLEDGMENT

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