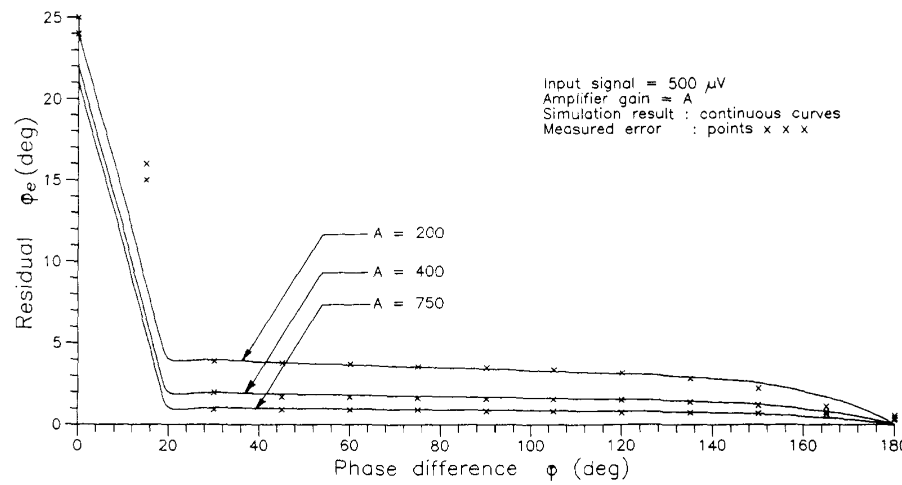

Fig. 6. Extent of phase compensation as a function of amplifier gain *A*.

effect [7]. The scheme can also be successfully employed in automatic test equipment involving ac bridges [8].

V. Conclusion

It has been demonstrated that using feedback technique for phase compensation in a PSD, the amplitude of the measurand can be got directly without the need for a post-processing of the in-phase and quadrature components. Experimental results presented serve to establish the easy applicability of the method to obtain a high degree of phase compensation coupled with a fine resolution. Quantitative comparison of the extent of compensation obtained experimentally with that estimated by PC-simulation indicates good agreement.

Acknowledgment

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A Fiber-Optically Triggered Avalanche Transistor

R. Jacob Baker, Gregory T. Perryman, and Phillip W. Watts

***Abstract*—A silicon bipolar transistor operating in the avalanche region is optically triggered into secondary breakdown. This transistor has been given the name fiber-optically triggered avalanche transistor (FOTAT). The FOTAT acts as an optical power discriminator. That is, secondary breakdown occurs when the triggering optical power exceeds the triggering threshold of the FOTAT. This secondary breakdown is seen as a negative resistance between the collector and emitter. High voltage (> 100 V) nanosecond transition duration pulses are generated using this negative resistance.**

I. Introduction

Avalanche transistors have found many uses in the design of instrumentation [1]–[4], but some problems exist when trying to use these transistors in electro-optic instrumentation. Time jitter requirements for this instrumentation can be much more stringent than in electrical instruments. The jitter developed when triggering these transistors electrically is mainly due to the stray inductance and capacitance. Also, when trying to generate a trigger from an optical signal a photodetector of some sort is usually required. A fiber-optically triggered avalanche transistor (FOTAT) can help solve both of these problems. By injecting the light directly into the transistor, not only can the secondary breakdown mechanism be triggered, but the jitter is theoretically nonexistent.

The optical triggering of an avalanche transistor was first shown by Thomas and Coleman [5]. A lens was used to focus part of a laser signal onto a transistor die to start the second breakdown process. This method of triggering is difficult to incorporate into a portable piece of instrumentation due to the alignment necessary in

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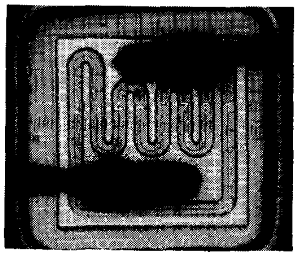
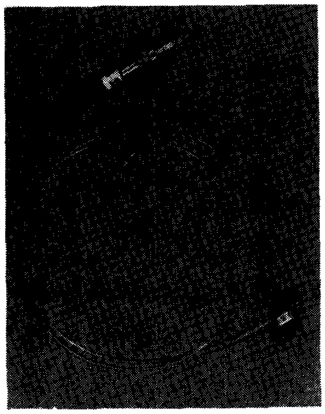


(a)



(b)

Fig. 1. (a) Epitaxial transistor used as a FOTAT. (b) Packaged FOTAT.

directing the laser signal and the requirement that the optical source be close to the transistor. For these reasons, the optical triggering of an avalanche transistor has been used very little. With the maturing of fiber optics within the last decade these problems can be eliminated. Fig. 1(a) shows the epitaxial transistor used as a FOTAT. The top of a transistor unit, packaged in a metal TO-39 type package, is removed. This exposes the transistor die. One end of an optical fiber is cleaved, positioned over the die, and epoxied in place, while the other end is terminated with a fiber optic connector. The result, shown in Fig. 1(b), is a versatile device that can be used in electro-optic equipment, performing functions from that of a nonlinear detector to that of an optically triggered electrical pulse generator.

II. Device Operation

The static characteristics of a bipolar transistor, as shown in Fig. 2, while operating in the avalanche mode, are given by (1a)–(1d),

$$I_C = (\alpha I_E + I_{CBO})M \tag{1a}$$

$$I_E = I_{ES}(e^{qV_{BE}/nkT} - 1) \tag{1b}$$

$$I_C = I_E + I_B \tag{1c}$$

$$V_{BE} = I_B(R_B + r_{bb}). \tag{1d}$$

The base current, I_B, is assumed to be flowing out of the base. The collector current, while operating in the avalanche region, is called the leakage current, I_L.

As the collector–base junction becomes reverse biased a point is reached where avalanche multiplication, M, becomes greater than one. The empirical expression for avalanche multiplication of a p-n

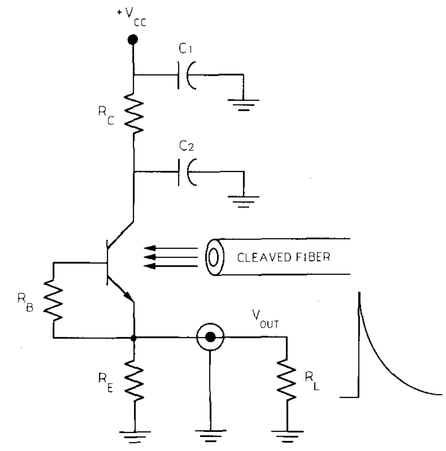


Fig. 2. FOTAT test circuit.

junction is given by

$$M = \frac{1}{1 - \left(\frac{V}{V_b}\right)^n} \tag{2}$$

where n is in the range of 2–6 for silicon, V is the potential across the junction, and V_b is the breakdown voltage of the junction. If R_B is zero, some simplifying assumptions may be made. The breakdown voltage V_b is approximately BV_{CBO}, the breakdown voltage of the collector–base junction with the emitter open. The emitter current is negligible compared to MI_{CBO} and can be assumed to be zero.

With the aid of Fig. 3 the dynamic operation of the transistor circuit shown in Fig. 2, with R_B equal to zero, may be described. A value of R_C is selected such that the static operating point of the transistor is at point A, a voltage just slightly below BV_{CBO} and at a current I_L. The value of R_C is typically > 100 kΩ. When the transistor is triggered the operating point moves to point B. Point B is determined by BV_{CBO}, R_L, and R_A, where R_A is the "on" resistance of the transistor. The negative resistance of the transistor while switching is given by the slope of the load line between points A and B,

$$\frac{1}{r_{neg}} = \frac{dI_C}{dV_{CE}}. \tag{3}$$

The transition duration from A to B is essentially independent of the load resistance. The upper limit of the load resistance is determined such that the transistor will not enter the active region when switching. The lower limit is set by the amount of power the transistor can dissipate without being destroyed. From point B the collector current decays exponentially with a time constant of $(R_A + R_L)C$ until reaching point C. This is the point where the transistor is no longer in second breakdown. The collector to emitter voltage at this point is not great enough to sustain the avalanche condition and is denoted by V_A. The collector current drops off quickly from point C to point D. From point D the collector capacitor voltage charges back to BV_{CBO} (point A).

The only parameter of operation not yet described analytically is the optical trigger pulse. Some problems exist in fully characterizing the effects of this pulse. The emitter and base metalizations shown in Fig. 1 present the first problem. The etched area between

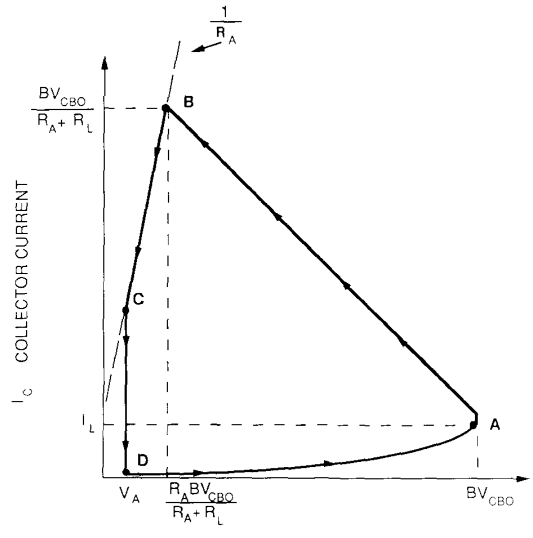


Fig. 3. *I–V* Characteristics of FOTAT.

these contacts is the only area where the light can penetrate the semiconductor and generate carriers. The position of the fiber with respect to the transistor will also have a part in determining the actual intensity of light radiated on the junction. If the intensity of light striking the semiconductor can be determined, the continuity equation can be used to determine the transport and decay of carriers, that is,

$$\frac{dn}{dt} = D\frac{d^2n}{dx^2} - \frac{n}{\tau} + f(x, t) \tag{4}$$

where $f(x, t)$ is the carrier generation function, D is the carrier diffusion constant, n is the carrier concentration, and τ is the mean carrier lifetime. The carrier generation function for single photon absorption is given by [6],

$$f(x, t) = \frac{q\alpha_1 I}{h\nu_1} \tag{5}$$

where α_1 is the single-photon absorption coefficient, q is electron charge, $h\nu_1$ is the energy of an incident photon, and I is the intensity of light incident on the semiconductor. The optical penetration distance, which is a function of wavelength and material type, is also a factor which is difficult to determine under these circumstances.

Because of the difficulty in determining the intensity of light radiated on the junction and the optical penetration distance, the optical trigger will be characterized by the optical power required to start the second breakdown process. This will allow the greatest flexibility when designing instrumentation around these devices.

III. Experimental Results

For the experimental tests the circuit shown in Fig. 2, with $R_B = 0$, $R_L = 50\ \Omega$, $R_C = 10\ \mathrm{M}\Omega$, $R_E = 510\ \Omega$, $C_2 = 100$ pF, was used. A 2N3742 transistor was used because it had a large die area, approximately 600 μm^2. Other transistors may be used as well, provided that the avalanche breakdown occurs in them before the punch-through effect. The value of V_{CC} was typically 900 V. This value of voltage should be set very close to the breakdown voltage of the transistor so as to keep leakage current to a minimum.

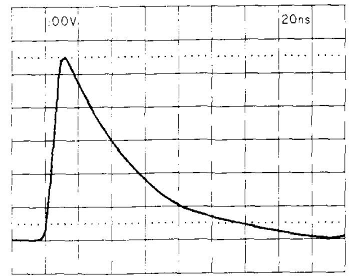


Fig. 4. Output pulse of FOTAT—100 V/div and 20 ns/div.

The output of this circuit into a 50-Ω load is shown in Fig. 4. The output amplitude is approximately 500 V with a first transition duration of about 10 ns. The optical trigger pulse is a 1.0-ns FDHM, Gaussian, at 806 nm, Fig. 5. This optical pulse is coupled to an attenuator, through a 50/125 graded index fiber, for adjustment of the optical power. The output of the attenuator is connected through a 50/125 graded index fiber, to a beamsplitter. The purpose of the beam splitter is to split the light pulse into two parts; one for monitoring the optical amplitude and the other for triggering the FOTAT.

Monitoring the optical amplitude is accomplished by taking 2% of the light pulse, one side of the beamsplitter, and converting it to an electrical pulse for display on channel one of the 7104 oscilloscope. The amount of optical power used for triggering can be calculated using the responsivity of the P6701 detector and the beamsplitter ratio. The other output of the beamsplitter is coupled to a 100/140 graded index fiber. This fiber is connected through an xyz translation stage to the transistor under test. The electrical output of the FOTAT is displayed on channel 2 of the 7104.

It has been found that positioning the fiber at different places above the transistor changes the amount of power needed to start the second breakdown process. The main objective in positioning the fiber above the transistor is to select the location where the optical power required to trigger secondary breakdown is a minimum. This would allow triggering from a lower power source. The xyz stage was used for positioning the fiber at different locations above the transistor. The distance between the fiber and die was approximately 20 μm.

The required optical power to trigger the FOTAT versus fiber position is shown in Fig. 6 for three transistors. These positions correspond to labeled positions shown on the transistor die in Fig. 1. The curves in Fig. 6 represent the most general characteristics of a total of 10 2N3742's used as FOTAT's with additional curves providing no additional information. Qualitatively, position 4 appears to be the optimum place for positioning the fiber.

The optical pulse duration did have an effect on whether the FOTAT did or did not trigger as the incident optical power became close to the threshold. This means that the energy in the pulse becomes the main factor determining whether the FOTAT will fire when using fast (< 1 ns) pulses at optical powers close to threshold. Also the leakage current through the transistor had some effect on the firing threshold. Increasing the leakage current caused a lowering of the threshold.

Other transistors, such at the 2N2222, were used as FOTAT's. The triggering optical power, the output amplitude, and transition duration varied among different transistors. For instance, the 2N2222 required approximately 15 mW to trigger. The output amplitude was > 100 V, with a first transition duration of < 1 ns.

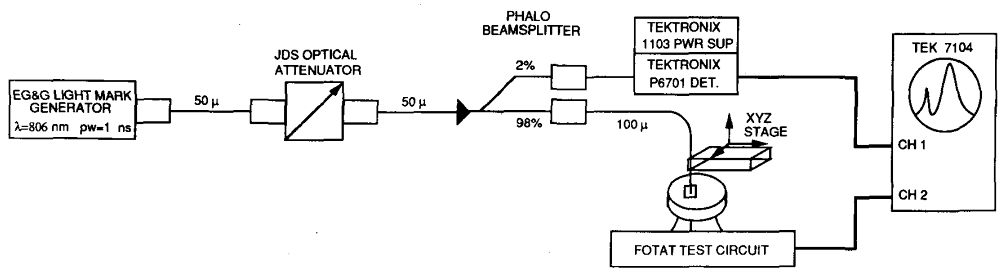


Fig. 5. Test setup used to determine triggering optical power.

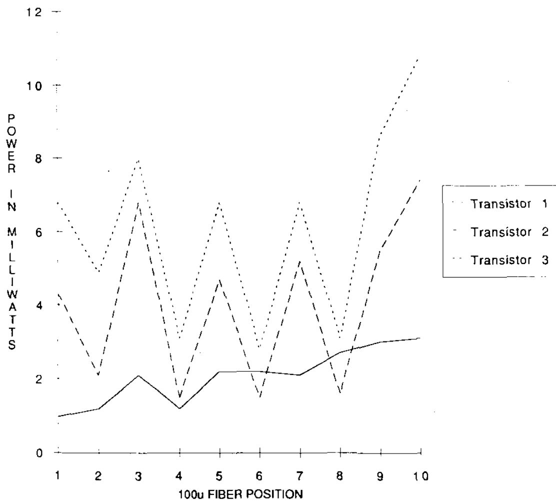


Fig. 6. FOTAT optical input power requirement versus fiber position.

IV. Concluding Remarks

The purpose of this paper was to present the idea of a FOTAT so that the device can be used in the design of electro-optic instrumentation. This device was shown to provide an effective method of generating fast transition duration electrical pulses from an optical signal.

Future work will be concerned with the device physics, as well as circuit design methods to exploit the operation of these devices. Problems such as the dependence of pulse duration on triggering and the dependence on leakage current will also be investigated.

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Recent Developments in the PTB RF Standard Attenuation Measuring Equipment

Dieter Stumpe

Abstract—**The frequency range of the RF standard attenuation measuring equipment at the Physikalisch-Technische Bundesanstalt (PTB), Germany, has been extended up to 40 GHz in the waveguide bands *R* 220 and *R* 320. The total uncertainty of the system is estimated to be equal to or smaller than 0.002 dB for a 30-dB attenuation step.**

I. Introduction

The standard equipment for carrying out attenuation measurements at the PTB, Braunschweig, works on the principle of the power ratio method applying dc substitution [1]. For the lower GHz range this equipment has been described in several papers [2]-[4]. It has the advantage of simplicity over all the other methods where mixers and local oscillators are used (e.g., IF and AF substitution techniques). Attenuation values up to 30 dB can be measured with small uncertainties.

In recent years the demand for attenuation calibrations at frequencies above 18 GHz traceable to national standards has increased because an increasing number of commercial and military communication links and radar systems are operated at frequencies between 18 and 40 GHz. The frequency range of the standard equipment for attenuation measurements at PTB has therefore been extended up to 40 GHz in two waveguide bands (*R* 220, *R* 320). This development is described in the paper.

II. The PTB Standard Equipment for Precise Attenuation Measurements

A block diagram of the standard equipment forming a waveguide system working on the principle of the power ratio method using dc substitution is shown in Fig. 1, and a more detailed diagram of the substitution section in Fig. 2.

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