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Performance of Optically Coupled Microwave Switching Devices

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***Abstract*—The performance of optically coupled microwave switching devices for pulse generation or other applications is detailed. The bias dependence of the RF power transfer is presented for a range of operating frequencies, thereby establishing the bias conditions required for a given ON/OFF ratio and insertion loss. Limits on peak RF power level and pulse repetition rate, as well as limitations arising from harmonic distortion and shot noise, are also examined.**

I. Introduction

THE RECENT EMERGENCE of solid-state optical device technology has made possible new microwave devices that are hybrids of conventional microwave technology and the newer optical technology. For the most part, such devices proposed to date use lightwaves to control the behavior or regulate the characteristics of some microwave element, be it an oscillator [1], [2], a switch [3], [4], or some other microwave device [5]. However, one can also envision a new class of microwave components wherein lightwaves are used not for control, but rather for the coupling of microwave energy from one point to another. Thus lightwaves would be used in a fashion analogous to that of the "opto-isolator" employed in lower frequency circuitry for some time.

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A component of this type was recently proposed by MacDonald and Hara [6], [7] for use as the crosspoint element in a video-signal switching array. The switch was based on the detector-bias dependence of the coupling between an optical source/detector pair. A very attractive feature of this switch for such RF signal routing is that it confines the RF energy to a narrow optical path. This allows the achievement of nearly zero signal cross-coupling even in highly compact switching arrays.

Independent of this work, we proposed [8] the same switching concept as the basis of a microwave gate for pulse generation and other applications. Here, the attractiveness of the switch results from its extremely high ON/OFF ratio and reverse isolation, as well as from the fact that its input impedance is completely independent of switching state. In pulse radar applications where a switch is used to gate a microwave source, for example, a high ON/OFF ratio and a high reverse isolation can lead to improvements in sensitivity and jamming immunity. A state-independent input impedence means that the problem of oscillator "pulling" is eliminated, which is crucial in phase-sensitive radar designs.

In the present paper, we report experimental results on the performance of such optically coupled microwave switches relevant to a variety of applications. We begin in Section II by considering RF power-transfer capability which determines the ultimate insertion loss of the switch. In Section III, we examine the ON/OFF ratio achievable under various operating conditions. Section IV deals with

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limits on microwave power level and repetition rate, as well as limitations arising from harmonic distortion and shot noise. In Section V details are given on the design of a switch suitable for microwave gating applications and the generation of short microwave pulses with such a device is demonstrated. Finally, conclusions are given in Section VI.

II. Microwave-Power Transfer Capability

By way of review the basic switching concept is illustrated schematically in Fig. 1. The switch is composed of two sections which are isolated from each other at microwave frequencies by proper shielding. In the input section, the microwave signal acts to intensity modulate the light emitted by an optical source (in the present case a laser diode) at the microwave rate. The modulated lightwave is then coupled to an optical detector (a p-i-n or avalanche photodiode) in the output stage where it is demodulated. A bias control signal governs sensitivity of the detector, thereby permitting continuously variable attenuation or ON/OFF switching to be achieved.

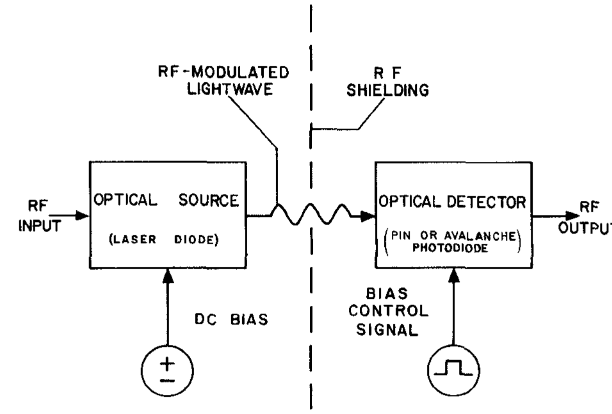

Fig. 1. Schematic representation of the microwave switch.

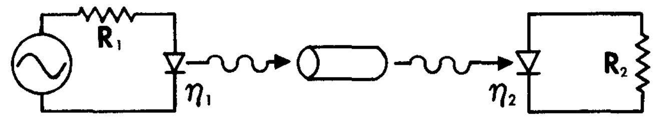

Fig. 2. RF power transfer.

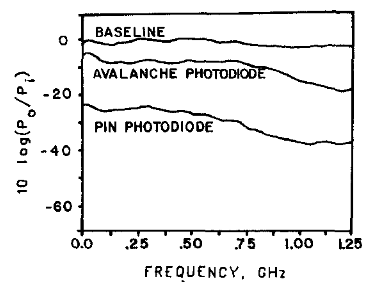

Fig. 3. RF power transfer ratio as a function of frequency for both the p-i-n and avalanche photodiode detectors. ($P_i = -2$ dBm.) The uppermost curve shows the power transfer with the input connected directly to the output of the measurement system (test device removed).

An important consideration for gating applications is the insertion loss of the switch, i.e., the microwave power loss in the ON state. The various components of this loss are shown in Fig. 2 for a fiber-coupled laser-diode/photodiode pair. As indicated, we consider the case of "direct" modulation wherein the laser is modulated by superposing the RF input signal on the laser bias. In addition to any mismatch loss at either the input or output (which could be "tuned out" by reactive matching), there exists the inherent loss due to electron/photon conversion at the laser diode and photodiode and the optical coupling loss between these elements. Conversion at the source for an ac signal is expressed by the differential quantum efficiency η_1. For currently available GaAlAs double-heterostructure laser diodes capable of continuous room-temperature operation, a typical low-frequency value for η_1 is 20 percent. Conversion at the detector is expressed by the quantum efficiency η_2, which for typical Si p-i-n photodiodes is about 60 percent at the optical wavelength of the GaAlAs laser (~820 nm). Because fiber-induced dispersion and attenuation are negligible over the very short distances needed in the present application, fibers having a very large numerical aperture can be used. Such fibers allow approximately 60 percent of the emitted photons to reach the detector. Since the amplitude of the microwave signal is proportional to the number of electrons per second involved in both conversions, the minimum insertion loss to be expected for this device without employing avalanche gain is 23 dB.

The measured power transfer ratio (ratio of the microwave output power P_o to microwave input power P_i) is shown in Fig. 3 for a directly modulated RCA C30130 laser diode (optical power$\simeq$2 mW) and two different detectors: an HP 5082-4203 p-i-n photodiode and a TIED 56 avalanche photodiode. For these and all subsequent results no matching circuitry was employed. The generator and load impedances were both 50 Ω and P_i is defined as the available input power, i.e., input power to a 50-Ω load. This means that the quoted transfer ratios are somewhat lower than could be achieved under matched conditions. (However, mismatch-loss measurements showed that the improvement from matching would typically be only 3 dB over the frequency range of interest.) The lower frequency results in Fig. 3 confirm that an insertion loss of approximately 23 dB can be achieved without avalanche gain. At higher frequencies the insertion loss increases due to the rolloff of the laser's frequency response. With the avalanche photodiode biased for a gain of 20 dB, this loss is reduced to about 8 dB at lower frequencies and to 12 dB at 1 GHz. It should be mentioned here that the level of avalanche multiplication in Fig. 3, as well as the peak levels in Fig. 4 to follow, were limited thermally. Due to heating, further increasing the photodiode bias did not result in increased power transfer. In order to prevent possible damage to the photodiode in these measurements, the switch was operated in a quasi-continuous mode wherein it was held in its ON-state for only a few seconds at a time. Further consideration of thermal limitations will be given later along with results illustrating the improvement possible for low duty-factor operation.

Reverse-isolation measurements were also made across the same frequency range for both switches by reversing the input and output ports. ("Reverse-isolation" refers to

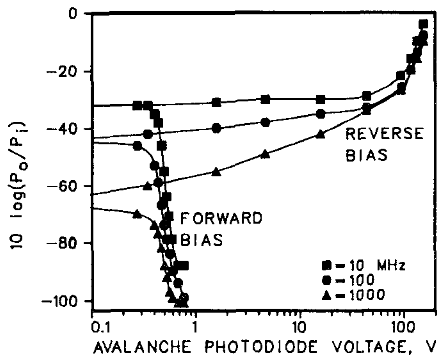

Fig. 4. RF power transfer ratio as a function of bias voltage for the avalanche photodiode at three different RF frequencies. The lower border of the graph represents the measurement system noise limit. ($P_i = 0$ dBm.)

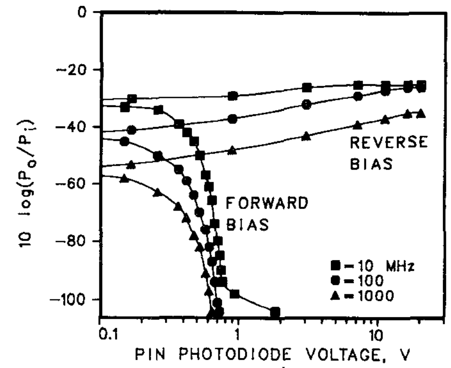

Fig. 5. RF power transfer ratio as a function of bias voltage for the p-i-n photodiode at three different RF frequencies. The lower border of the graph represents the measurement system noise limit. ($P_i = 0$ dBm.)

the power transfer ratio in the reverse direction.) For this measurement the RF power level was increased to 10 dBm. The reverse isolation was found to be at least 114 dB, the measurement system limit, across the entire frequency range regardless of the bias conditions of the switch.

III. Switching Characteristics

A practical microwave gate must of course exhibit good switching characteristics in terms of a high ON/OFF ratio (ratio of RF output power in the ON state to that in the OFF state). Furthermore, systems applications often require that the switching function be obtainable with some limited excursion in bias level. Thus in this section we examine the bias-dependence of the RF power transfer.

The switching characteristics for the p-i-n photodiode configuration are shown in Fig. 5 where the transfer ratios at three different frequencies have been plotted as functions of bias voltage. Confining our attention to reverse biases for the moment, we see that the ON/OFF ratio achieved between 0 and 20 V is only about 6 dB at 10 MHz, but that this ratio increases to 20 dB at 1 GHz. This frequency dependence is basically the result of the contribution of diffusion to the photocurrent. The diffusion component is caused by carriers that are generated outside of the depletion region and then diffuse into the depletion region. The ac component due to the diffusing carriers is reduced at high frequencies since few carriers are able to reach the depletion region within an RF period. Thus the component due to generation within the depletion region dominates and the photocurrent becomes more sensitive to the bias-dependent depletion region width.

Although adequate for many applications, the 20-dB ON/OFF ratio obtained at 1 GHz is still small compared to what can be achieved with a low forward bias. In particular, examination of Fig. 5 reveals that the transfer ratio drops to the measurement system noise floor as the forward bias approaches about 1 V, thereby allowing an ON/OFF ratio of over 70 dB to be achieved at 1 GHz. While carrier diffusion and depletion width variations also play a role in determining the response under forward bias, the drastic reduction in the power transfer is primarily the result of the following. While the separation of photogenerated electron-hole pairs by the potential barrier causes a current in one direction, the injection of carriers over the barrier caused by the forward bias produces a current in the opposite direction. Increased photogeneration increases the forward bias, so that changes in the amount of photocurrent produce compensating changes in the amount of injection current. This greatly reduces the change in the total current seen at the terminals and, hence, the ac response.

Considerable improvement in the switching characteristics can be obtained by making use of carrier multiplication at high reverse bias. This is illustrated in Fig. 4 where the transfer ratio is plotted for the case of the avalanche photodiode detector. The figure shows that the transfer ratio increases by approximately 25 dB as the reverse bias approaches the diode's avalanche breakdown voltage ($\sim$170 V). Due to the enhanced response an ON/OFF ratio of at least 90 dB can be achieved at 1 GHz by switching between reverse- and forward-bias states, while a ratio of nearly 50 dB can be obtained even without forward bias. Performance is also greatly improved with respect to the insertion loss which drops to 8 dB for the 1 GHz results.

The tradeoff for this improvement in performance is the requirement for a much higher operating voltage as well as a substantial reverse current. While the current drawn at the forward bias levels shown in Fig. 4 may be as much as 10 mA, this presents no problem since the voltage is low. At the avalanche voltage, however, such continuous current can exceed the thermal dissipation capabilities of the diode making pulsed operation necessary.

A circuit model for the RF switching behavior of photodiodes is given elsewhere [7]. In what follows we focus on various limitations to the performance of the switch.

IV. Limitations

The limitations of the switch can be divided according to whether they arise primarily from the laser diode in the input section or from the photodiode in the output section. We begin by considering the output section. The results below are for a switch composed of a GOLS-1 (General Optronics) laser diode and a TIED 55 avalanche photodiode. Except as noted, the operating frequency was 2 GHz.

Fig. 6 shows the transfer ratio as a function of the

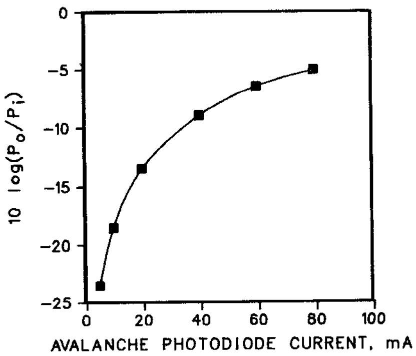

Fig. 6. Dependence of RF power transfer of avalanche current under low duty-factor pulsed conditions. ($f=2$ GHz, $P_i=0$ dBm.)

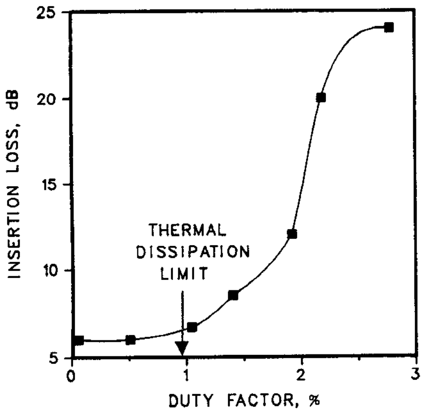

Fig. 7. Dependence of insertion loss on duty factor under high-level avalanche operating conditions. (Diode voltage and current are 165 V and 70 mA, respectively. $f=2$ GHz, $P_i=0$ dBm.)

avalanche photodiode current measured under low duty-factor pulsed conditions. (The transfer ratio at low currents in this figure is somewhat less than in the previous figures due to the higher operating frequency for Fig. 6.) It can be seen that an insertion loss as low as 5 dB can be obtained by operating the detector at an avalanche current equal to 80 mA. In order to avoid exceeding the 0.1-W thermal dissipation rating of the diode, however, one is limited to a duty factor of 1 percent or less at this current. The degradation in insertion loss that occurs as this limit is exceeded is quite severe, as illustrated in Fig. 7. Therefore, when the optical coupling is good, one can make use of avalanche multiplication for reducing insertion loss only when the duty-factor is low. A benefit that *can* be gained from multiplication for high duty-factor or continuous operation is a reduction in the optical signal level needed for a given insertion loss. Since the laser diode is by far the most expensive component in the switch, this could lead to a substantial reduction in cost. It should be noted, however, that multiplication cannot effectively compensate for an optical source that has high output power but a low differential quantum efficiency since the thermal limitation is associated with the *average* optical power level.

Another consideration related to the use of avalanche is the amplification of shot noise by the multiplication process. The measured noise power output of the switch is shown in Fig. 8 as a function of photodiode current. As is

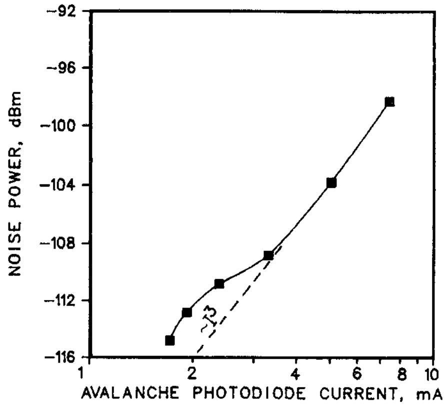

Fig. 8. Noise power output as a function of current. Results are for a 1-kHz bandwidth at 1 GHz.

well known [9], the noise power increases approximately as the cube of the multiplication factor, and, hence, as the cube of the current. Since the signal power only increases as the square of the current, the signal-to-noise ratio during the ON-state of the switch degrades as the current is increased. For applications involving the switching of wide-band signals, this noise could pose a problem. The noise power within a 10-percent bandwidth at 2 GHz, for example, would be -46 dBm at a 7-mA bias. According to Fig. 6, the insertion loss at 2 GHz is 20 dB for this bias. Hence, the signal-to-noise ratio for a 0-dBm input signal would be only 26 dB. This noise component is not present, of course, when the switch is in its OFF-state. Thus it should not produce a problem when the switch is used to gate a microwave source. For example, this noise would not mask the reception of target returns between pulses in a pulsed radar system.

The limitations to the performance of the switch that arise in the input section are associated with the modulation characteristics of the laser diode, both in terms of nonlinearities and frequency response. One of the most basic of these is the peak microwave-power handling capacity. As discussed earlier, a high differential quantum efficiency is desirable for low insertion loss. This means that the slope of the optical power versus current characteristic should be as large as possible beyond threshold. A large slope implies, however, that the ac response of the laser diode is linear only for small current swings. Thus the RF output will saturate at quite low input levels.

The measured power-saturation characteristic of the switch is shown by the upper pair of curves in Fig. 9, which represent results under avalanching (solid curve) and non-avalanching (dashed curve) detector bias conditions. To facilitate comparison the nonavalanching results have been shifted to coincide with those for the avalanching case. It can be seen that the RF output saturates when the input reaches -5 and 0 dBm for the avalanching and non-avalanching cases, respectively. The fact that the curves for the two cases are essentially the same illustrates that although the avalanche diode influences the nonlinearity of the characteristic, the saturation is caused by the laser diode.

An associated consideration is the amount of harmonic

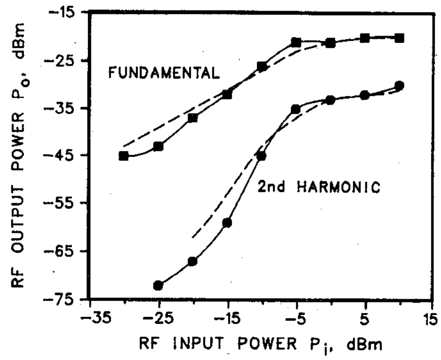

Fig. 9. Variation of fundamental and second harmonic output power with input power level. Solid curve through symbols shows results for an avalanche current equal to 5 mA. Dashed curve (symbols omitted) shows results for no avalanche shifted upward by 19 dB. (f=2 GHz.)

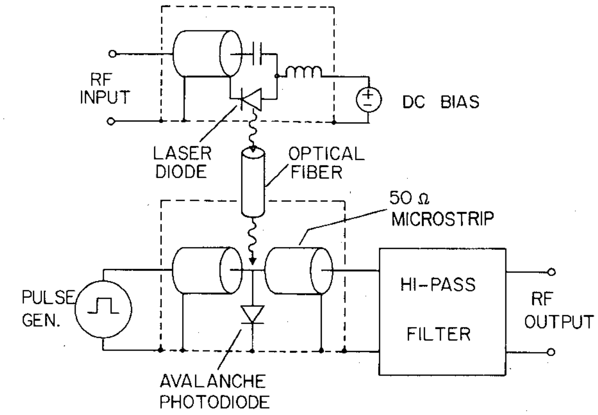

Fig. 11. Schematic diagram of a configuration of the switch suitable for high-speed gating of microwave signals.

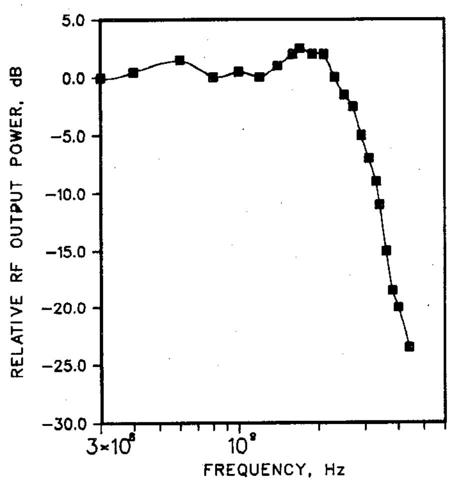

Fig. 10. Frequency response of the switch. (P_i =0 dBm.)

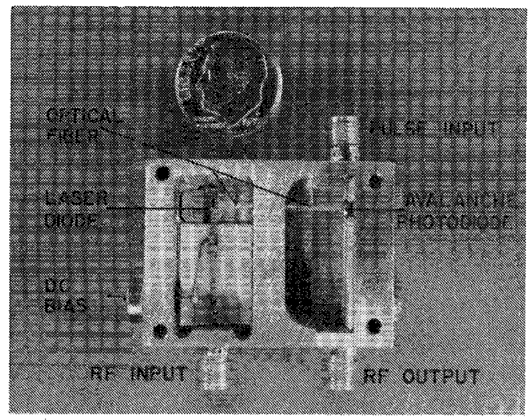

Fig. 12. The actual switch used for the results presented in Figs. 6–10.

distortion produced by nonlinearities in either the laser or photodiode. The output power at the second harmonic is shown in the bottom portion of Fig. 9 for the same two bias conditions (the low bias results are shifted as before). It can be seen that the relative second-harmonic distortion (second harmonic power divided by fundamental power) is almost −30 dB for low input signal levels, but that the distortion increases to about −13 dB as saturation is approached. Again, the similarity of the curves for the two bias conditions indicates that the distortion is almost entirely caused by the laser diode.

Finally, we examine the upper frequency limit of the switch. A log–log plot of the frequency response is shown in Fig. 10 for a GOLS-1 laser diode. The detector was a TIED-55 avalanche photodiode. It can be seen that the response is constant within ±1 dB from 300 MHz to 1.5 GHz. Following a slight enhancement at 2 GHz the response falls off very sharply so that at 4 GHz the power has already dropped by 20 dB. Hence, the practical frequency limit for this switch is about 3 GHz.

V. Microwave Gate Configuration

A schematic diagram showing the particular configuration of the switch used to obtain the results presented in Figs. 6–10 is shown in Fig. 11. The output of the directly modulated laser diode is coupled through an optical fiber to an avalanche photodiode which is connected in shunt with a microstrip line. The shunt arrangement is attractive because it permits excellent heat sinking of the photodiode. In addition, this configuration is suitable for high-speed pulsed operation since it allows the bias pulse to be brought in via a transmission line from one side of the circuit while the RF output is taken from the other side. The high-pass filter prevents pulse transients from reaching the output.

The actual switch is shown in Fig. 12. The laser diode is a GOLS-1. This device is available as an exposed laser-diode chip mounted on a small heat sink. A bonding wire connects the chip to a metal strap that is fastened to a ceramic standoff which allows for low-parasitic connection to the microstrip line. The laser output is coupled to a plastic optical fiber 16 mils in diameter (Dupont PFX-PIR140) which is routed through a small hole connecting the otherwise isolated input and output sections. The fiber is mated to a TIED-55 avalanche photodiode. The lens was removed from the pill-style package of the TIED-55 and was replaced by a ring through which the fiber was routed. This allowed the fiber to be positioned slightly above the surface of the photodiode chip. An MF-420-BPG-7949 (Centre Engineering) button filter was used to prevent RF leakage through the laser bias lead and a 91-pF ceramic chip capacitor (ATC) provided a dc block. The RF-input and RF-output/pulse drive lines are 50-Ω alumina microstrip

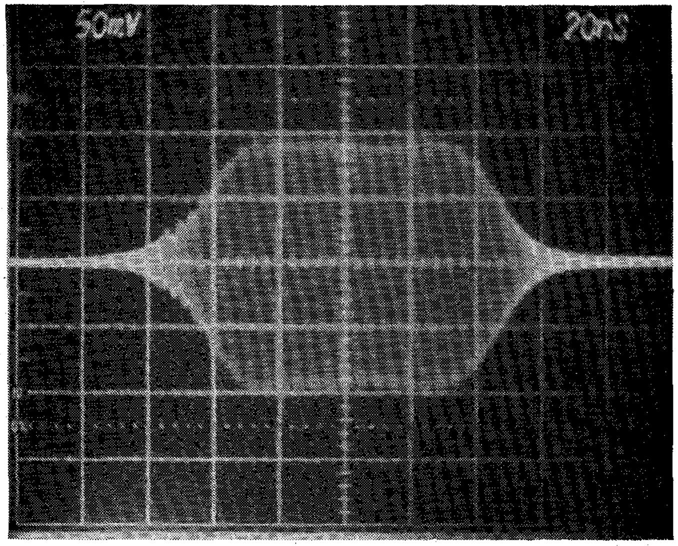

Fig. 13. Pulsed RF output achieved by using such a switch to gate a 0.5-GHz RF source. Similar results were obtained for frequencies as high as 3 GHz.

transmission lines. The ground plane of the latter was attached to the sidewall of the output cavity. The anode tab of the pill package was soldered into a hole in the sidewall to provide good heatsinking. The depth of the hole was chosen so that the underside of the top flange of the package contacted the microstrip surface. The flange was soldered to the microstrip line on each side.

The gating of an RF source with a switch of this type is illustrated in Fig. 13. The bias levels for the ON and OFF states were 0 and 165 V, respectively. The pulse repetition rate was 1 kHz. The switching time for the OFF-to-ON and ON-to-OFF transitions in this figure (about 20 ns each) were limited by the rise and fall times of the pulse generator itself. Thus, faster switching should be possible. The operating frequency for the results in Fig. 13 was 0.5 GHz and was chosen to permit the RF output signal to be viewed on an oscilloscope of this bandwidth. Spectral analysis of the output revealed, however, that comparable performance was possible for frequencies up to the 3-GHz limit of the switch.

VI. Conclusion

In the preceding sections we have examined the performance of several prototype optically coupled microwave switches. These devices were composed of currently available laser-diode/photodiode pairs and made use of direct RF modulation of the laser diode.

The results show that such switches can provide ON/OFF ratios of 20 dB at 1 GHz even under highly restricted detector bias conditions (low-level reverse bias only, with no avalanche). By making use of avalanche at high reverse bias an ON/OFF ratio of 50 dB can be achieved. Ultrahigh ON/OFF ratios are possible if forward bias is allowed. By utilizing both avalanche- and forward-bias conditions, an instrument limited ON/OFF ratio of over 90 dB was demonstrated. Similarly the observed reverse isolation of the switch, 114 dB, was limited only by the measurement system itself.

While carrier avalanche is optional for realizing high ON/OFF ratios, it is a necessity for low insertion loss. Versions of the switch incorporating (nonavalanching) p-i-n photodiodes were found to introduce 32 dB of insertion loss at 1 GHz while switches that incorporated avalanche photodiode detectors introduced as little as 5 dB of loss at frequencies as high as 2 GHz. Due to thermal limitations, however, the use of avalanche will be limited to low duty-factor operation in most applications. A notable exception would be that of a multidetector configuration of the switch in which the optical coupling loss to each individual detector element is high.

Amplification of shot noise by the avalanche process is a further consideration when the signal-to-noise ratio in the ON-state is of concern. For applications involving a wide bandwidth, say 200 MHz, the results show that the signal-to-noise ratio at a moderate multiplication level would be only 26 dB for a 1-mW input signal. Because the noise increases more rapidly with multiplication factor than does the signal, the amplified shot noise would be of particular concern in signal routing applications requiring high multiplication levels.

Saturation of the output power was found to occur for an input level of about 0 dBm. This saturation is a result of the laser diode's response and places a limit on the peak power handling capacity of the switch. Harmonic distortion is also produced almost entirely within the laser diode. In these experiments the relative second-harmonic distortion rose from -30 dB at an input power of -25 dBm to -13 dB at 0 dBm. The amount of distortion depends strongly on operating conditions as well as device geometry [10], and considerably lower levels should be achievable.

The upper frequency limit of the switch was found to be about 3 GHz due to the rapid falloff in the frequency response that is characteristic [11] of directly modulated laser diodes. While some RF power transfer is possible even at X-band frequencies [12], the insertion loss at these frequencies would be extremely high. Operation at frequencies far above 3 GHz should eventually be possible, however, through the use of techniques for enhancing the direct-modulation response [13] or through the use of external modulators [14].

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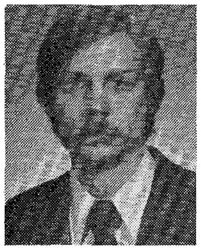

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Optoelectronic Microwave Switching via Laser-Induced Plasma Tapers in GaAs Microstrip Sections

WALTER PLATTE

Abstract—**This paper presents a new type of high-speed optoelectronic GaAs microstrip switch controlled by a pulse-operated laser diode via substrate-edge excitation. The exponential decay of photoconductivity across a longitudinal section of the microstrip forms a laser-induced electron-hole plasma wedge that works as a lossy tapered transmission line. The dynamics of carrier generation and recombination as well as the overall performance of the switch are quantitatively analyzed and optimized. This device is capable of switching with subnanosecond precision as well as with optical pulse energies in the order of 1 μJ. Theoretical and experimental results were found to be in good agreement.**

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I. Introduction

LASER-CONTROLLED solid-state microstrip switches (or optoelectronic switches) have gained much active interest within the last few years due to their picosecond

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