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A Broad-Band Optoelectronic Microwave Switch

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***Abstract*—A broad-band optoelectronic switch based on an avalanche photodiode is described. The microwave signal is supplied to the switch as intensity modulation on an optical carrier wave. Switching is achieved by reverse biasing the APD for the on-state and forward biasing for the off-state. Isolation of better than 80 dB is reported over a signal frequency range of 10 MHz to 1 GHz. In the same switch, isolation greater than 60 dB is observed up to 3 GHz. A turn-on time of 400 ns was observed without special techniques for discharging the junction, the turn-off time is much shorter.**

I. Introduction

OPTICAL techniques have been used recently to control microwave signals in a number of ways. One example is a variable-frequency GaAs FET oscillator controlled by means of optical radiation incident on the device [1]. The capacitance of the GaAs FET is influenced by the incident optical power, allowing optical control of the oscillation frequency. A second example is a switch that is operated by optical control of the RF impedance of a diode placed in the microwave signal path [2]. These configurations use an optical signal to control an electrical signal. In contrast, optoelectronic switches have been proposed using photodiodes as the switching elements [3]. These are controlled electrically while an optical signal is used to convey the information to be switched. A schematic circuit diagram of such a switch is shown in Fig. 1. The signal is supplied to the switch as an intensity modulation on an optical carrier. To place the switch in the on-state, a reverse bias is applied to the photodiode. The optical input is then detected and an electrical output signal is obtained across the load resistor R_L. To place the switch in the off-state, the photodiode is forward biased. The photodiode then acts as a low impedance element across the load resistor, so that very little of the photogenerated signal current can be extracted from the photodiode into the external circuit. A reduced level of signal therefore is observed at the output. The quantum efficiency of the photodiode can be reduced by forward bias and this process may also contribute to the isolation of the switch in the off-state.

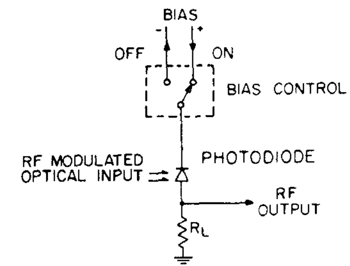

Fig. 1. Optoelectronic switch. When reverse biased, the photodiode detects the RF modulation on the optical input signal and produces an RF output across the load resistor R. When forward biased, the sensitivity of the photodiode drops and at the same time the photodiode acts as a low impedance bypass around the load resistor. Consequently much reduced RF output is obtained. Bias control can be achieved with a simple solid-state circuit.

Bias supply isolation inductances are not required with the optoelectronic switch because the signal is introduced optically. Impedance matching between the optoelectronic switch and external circuitry is accomplished readily for the on-state by choosing a suitable value for the load resistor R_L. Impedance matching in the off-state is unimportant because reflections of the optical signal are not influenced by the electrical matching conditions. Thus, in comparison to RF p-i-n diode switches, optoelectronic switches can be used in simpler circuit configurations.

An optoelectronic switch can have a higher isolation factor than a comparable microwave diode switch because of the reduction in the quantum efficiency that can occur

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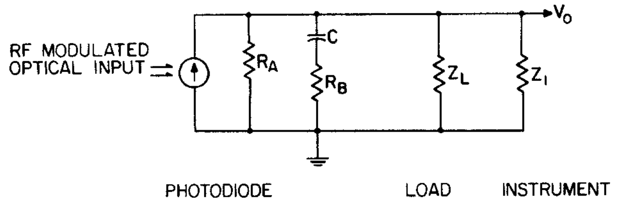

Fig. 2. Optoelectronic switch circuit model. The network formed by R_A, R_B, and C represents the internal impedance of the photodiode according to the bias conditions that are employed.

under forward biasing, which contributes to the isolation in addition to the decrease of the device impedance. For frequencies up to 245 MHz, an isolation of 80 dB has been reported for a p-i-n photodiode switch [4]. If an avalanche photodiode (APD) is used in place of the p-i-n photodiode, a third switching mechanism is provided through the loss of the avalanche multiplication process when the APD is forward biased. This mechanism provides additional isolation equal to the square of the avalanche charge multiplication factor. Further, the APD can be expected to perform well at frequencies above 1 GHz because of its small junction capacitance. In the following sections, we first present a simple circuit model of an APD optoelectronic switch and then report an experimental evaluation of such a device.

II. Circuit Model

An avalanche photodiode can be modelled as a current source that is proportional to the input optical signal power P_0, shunted by an RC network [5]. Fig. 2 shows such a model. The network formed by R_A, R_B, and C establishes the internal impedance Z_D of the photodiode according to the bias conditions that are employed. The signal observed by an external instrument with an input impedance Z_i that is connected across a load impedance Z_L used in conjunction with the photodiode can be computed from this model. The voltage V_0 that appears across the load is given by the expression

$$V_0(h\nu/e)\eta G P_0 Z_D \tag{1}$$

where

- h Planck's constant,
- ν the optical frequency,
- e the electronic charge,
- η the quantum efficiency,
- G APD gain factor.

The electrical signal power p_e delivered to the external instrument in response to the input optical signal is then found to be

$$P_e = \left| \frac{Z_L V_0}{Z_L + Z_D} \right|^2 \frac{Z_i}{|Z_i + Z_s|^2} \tag{2}$$

where Z_s is the source impedance formed by the parallel combination of Z_D and Z_L.

The isolation I of the optoelectronic switch is defined to be the ratio of the delivered electrical power when the diode is reverse biased to that when it is forward biased.

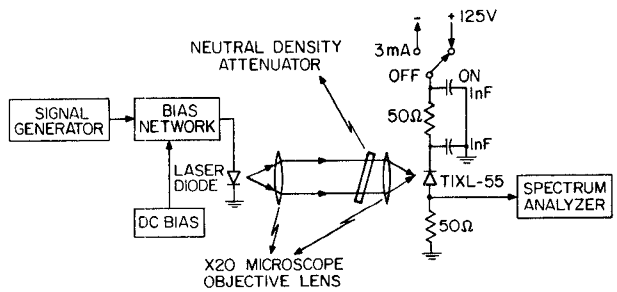

Fig. 3. Experimental arrangement. A commercial bias network was used to bias the laser diode. The output of the laser was focused onto the APD by two microscope objective lenses.

The following expression for I is thus obtained [5]:

$$I = \left[\frac{\eta_R}{\eta_F} \right]^2 G^2 \frac{|Z_{DR}|^2 \cdot |Z_i + Z_{SF}|^2}{|Z_{DF}|^2 \cdot |Z_i + Z_{SR}|^2}. \tag{3}$$

In (3), the subscripts R and F distinguish quantities appropriate to reverse and forward bias conditions, respectively.

Both the current multiplication factor of the APD and the ratio of its reverse and forward quantum efficiencies can play a significant role. It has been shown that for a commercial APD (TIXL-55) under practical operational conditions, the contributions to isolation resulting from quantum efficiency reduction, gain elimination and impedance reduction with the change from reverse to forward bias conditions are approximately 35, 25, and 20 dB, respectively [5].

The performance of an APD optoelectronic switch was determined experimentally in order to obtain a measure of the practical limits of currently available devices for switching high frequency signals. The following sections describe the experimental arrangement and results.

III. Experimental Arrangement

Fig. 3 shows a block diagram of the experimental arrangement. A single mode laser diode (HLP 2600U) was biased at 26 mA with a bias network (HP11590A) which also coupled the output of a signal generator to the laser. The RF modulation power was set at 40 mW for each measurement frequency. The output of the laser was attenuated as necessary by a neutral density filter and focussed by means of microscope objectives onto the APD (TIXL-55) optoelectronic switch. The reverse bias for the on-state was approximately 125 V, yielding a photocurrent gain factor of approximately 5. A forward current of 3 mA was used to establish the off-state. The RF output level of the APD was measured with a spectrum analyzer (HP8555A, 8552B, 141T) to obtain the on-state and off-state output signal levels. For frequencies above 2 GHz, a broad-band amplifier with approximately 20-dB gain was used to raise the RF signal in the off-state above the spectrum analyzer noise level.

In order to minimize RF leakage, the connections to the laser diode and APD were accomplished by soldering semirigid coaxial cables directly to the devices. Since the laser diode had a low-frequency resistance of approxi-

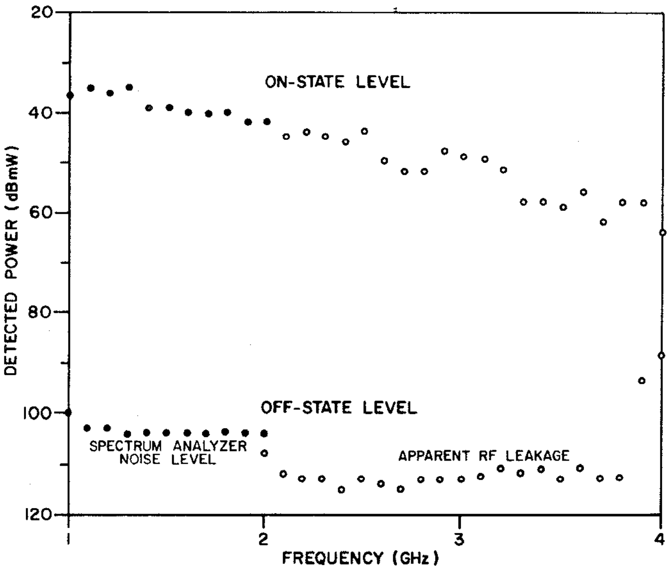

Fig. 4. Output power levels. The on-state and off-state RF power levels at the output of the APD (TIXL-55) optoelectronic switch are shown for frequencies above 1 GHz. The off-state level up to 2 GHz (filled circles) is that produced by the spectrum analyzer itself. Above 2 GHz (open circles), an amplifier was used to raise the signal input to the spectrum analyzer to a convenient level. The experimental parameters are listed below:

incident optical wavelength	= 820 nm
incident optical power	= 130 μW
reverse bias voltage	= 125 V
forward bias current	= 3 mA
modulation factor	< 0.5 at 1 GHz
	< 0.2 at 2 GHz.

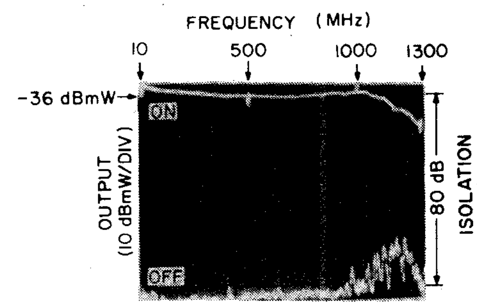

Fig. 5. Output power levels. The on-state and off-state RF power levels at the output of the APD (TIXL-55) optoelectric switch are shown. The experimental parameters are shown below:

incident optical wavelength	= 890 nm
incident optical power	= 41 μW
modulation factor	= 0.51
reverse bias voltage	= 154 V
forward bias current	= 2.6 mA.

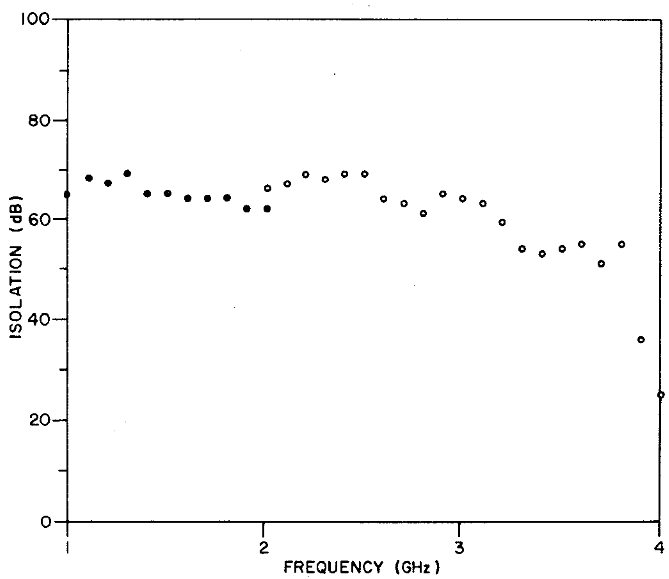

Fig. 6. Isolation. More than 60 dB of isolation is maintained up to and beyond 3 GHz. At least 50 dB of isolation is obtained for most of the frequency range shown.

mately 30 Ω, no series matching resistor was used. We were able to modulate the laser at frequencies above 6 GHz using this apparatus. This high-frequency modulation capability was confirmed with an OPFET detector [6] which provided an output level of approximately −80 dBmW at 6 GHz. Measurements of the isolation of the APD optoelectronic switch were taken at frequencies up to 4 GHz. Direct RF leakage into the switch circuitry interfered with the measurement of the switch isolation factor at higher frequencies. The following section describes the measurement results obtained by the experimental arrangement discussed above.

IV. Experimental Results

Fig. 4 shows the on-state and off-state RF power levels at the output of the APD optoelectronic switch. No postdetection amplifier was used for frequencies up to 2 GHz. The data points for this case are indicated by dots. It was determined that the off-state level shown in Fig. 4 for frequencies up to 2 GHz was the spectrum analyzer noise level by blocking the optical input to the APD and noting that the off-state level did not change. The data points for frequencies above 2 GHz are indicated by circles. These results were reduced to levels corresponding to that at the output of the APD by subtracting the gain of the amplifier. Since the off-state level for frequencies above 2 GHz did not change when the optical input to the APD was blocked, and since the postdetection amplifier raised the off-state signal above the noise level of the spectrum analyzer, we may conclude that Fig. 5 shows RF leakage around the switch. It does not represent detection of the optical signal by the photodiode. In particular, strong RF leakage appears for frequencies above 3.9 GHz, precluding measurements at higher frequency.

The ratio between in the on-state and off-state levels expresses the isolation of the APD optoelectronic switch. Fig. 6 shows the isolation corresponding to the data shown in Fig. 4. We see that more than 60 dB of isolation is provided from 1 GHz to above 3 GHz and more than 50 dB of isolation is obtained up to 3.8 GHz. The small discontinuity in isolation at 2 GHz results from the insertion of the broad-band amplifier for frequencies above 2 GHz. The measured isolation is function of the on-state level which decreases with frequency as shown in Fig. 4. This decrease most likely arises from the diminishing response of the laser diode at high modulation frequencies.

For completeness, an experimental result obtained from an earlier experiment at frequencies below 1.3 GHz [7] is shown in Fig. 5. A network analyzer was used to record this result. The same APD (TIXL-55) was operated at a higher reverse bias voltage (156 V), where the gain factor is approximately 20 according to manufacturer's specifications. The isolation is therefore higher than in the previous case. In consequence of the higher gain, the frequency response observed above 1 GHz for the on-state condition rolls off. The figure shows that more than 80 dB of isolation is maintained over the frequency range from approximately 10 MHz to 1 GHz. The apparent increase in leakage in the off-state above 1 GHz was produced by direct RF crosstalk caused by the experimental arrangement, which allowed some RF signal at these frequencies to leak around the APD optoelectronic switch.

It is apparent from the experimental results that the APD optoelectronic switch can provide more than 60 dB isolation over a broad frequency range from approximately 10 MHz to 3 GHz and that more than 50-dB isolation up to approximately 4 GHz can be obtained. The significance of the experimental results and some possible applications of such a switch are discussed in the following section.

V. Discussion

The upper frequency of operation of the APD optoelectronic switch at present appears to be limited primarily by the capability of laser diode light sources to respond to high frequency modulation. The frequency response of the switch can also be limited by the inherent capacitance of the APD, which is approximately 1 pF, but a comparatively flat response up to 3 GHz would be expected with our experimental configuration.

The practical high-frequency limit for direct modulation of injection laser diodes appears to be about 5 GHz according to small signal theory [8]. Judging from our present results, useful operation for switching frequencies up to at least 4 GHz is possible. By minimizing the laser diode package inductance operation up to the predicted 5 GHz should be achievable. However, the level of nonlinear distortion products appears to increase with modulation depth as well as frequency [8] and further work is required to determine the limits of practicality.

The most attractive application of the APD opto-electronic switch is in the construction of a broad-band crosspoint switching matrix [7]. Since the output from a single laser diode can be optically divided and distributed to each of an array of crosspoints consisting of APD opto-electric switches, RF crosstalk is eliminated among the distribution lines as well as between the distribution lines and output lines. Use of optical means to distribute the signal also provides the option to isolate the output lines spatially and thereby reduce RF crosstalk between them. Signal reflections into the power dividing network are independent of the states of the switches, in contrast to the situation with microwave power dividing networks and switches. Since switch isolations of 60 dB up to 3 GHz have been demonstrated, such matrices may be useful in many applications.

The APD optoelectronic switch operates over a broad bandwidth extending from below 10 MHz to above 3 GHz. Broad-band analog signals as well as high bit-rate digital signals can therefore be switched. Future application to broad-band communication networks and satellites can be readily envisaged. At present, optoelectronic switches are suited for circuit switching where switching speed is not a critical factor. The turn-on and turn-off times of the switch are determined by the discharge of the junction capacitance through the load resistance. Since the capacitance of the junction in forward bias is higher than in reverse bias, the turn-on time is the longest. We have measured a turn-on time of approximately 400 ns for the basic switch circuit under the experimental conditions for Fig. 4. The turn-on time can be reduced by employing additional components in the elementary circuit, for example by placing a switching device across the load resistor. Switching times comparable to RF p-i-n diodes may be possible and therefore such applications as time division multiple access (TDMA) communication satellite switching may arise in the future.

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