HIGH POWER MICROWAVE P-I-N DIODE INDUCTIVE DRIVING

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Abstract

Microwave p-i-n diode in phase shifting applications can be effectively switched to forward-bias by current spiking techniques and to reverse-bias via an energy storing inductor. This paper presents a design and analysis approach based on an inductive discharging circuit and first order p-i-n diode models. Experimental results, which support the theory, are also included, and a comparison is made to those available from conventional circuit investigations. High reverse current provided by external circuitry results in high speed switching, while reverse current provided by an energy storing inductor results in circuit simplifications, economy and higher reliability.

Introduction

Conventional p-i-n diode driving circuits include at least two semiconductor output devices, usually transistors[1-4] that switch the p-i-n diodes to forward or reverse-bias, depending on the input signal command (see Fig. 1). In order to obtain acceptable switching speeds for high power phase shifting applications, high current spikes are needed during both p-i-n diode transitions[4-5], as shown in Fig. 2. This, however, complicates the design of the driving circuitry, particularly the reverse-bias switching section, where a storing capacitor and two high voltage transistors with special characteristics must be used. Also, the current and voltage waveforms during the reverse-bias switching are strongly influenced by the nonlinear voltage change across the reverse-bias transistor[3] Q_2 in Fig. 1. Further, to incorporate short-circuit features in the driving circuitry, additional components will be needed[6].

In certain medium and high power applications, with moderate repetition rates, the reverse to forward-bias current ratio , that establishes the switching speed[5],needs not be very large. In such cases, a simpler driving circuit can be used. The reverse-bias transistor Q_2, for example, could be replaced by an inductor as suggested in a previous design review work[7] by the author. The inductor, preferably in toroidal coil form, stores energy during the forward-bias condition and provides a reverse current to discharge the p-i-n diodes during the reverse-bias transition.

This paper presents the main features of an inductive driver with a brief analysis of each region of operation. Experimental results are also presented and compared to those available from previous investigations on p-i-n diode driving circuits, primarily with totem-pole or complementary transistor outputs.

Inductive Driver Features

In the inductive driver, shown in Fig. 3, there is only one transistor in the output circuit. The other transistor has been substituted by the toroidal coil L_T. For medium and high power p-i-n diode drive amplifiers, the toroidal coil is more suitable than a solenoid for the following reasons:

1) When the toroid has a uniform winding, the magnetic lines of flux are almost entirely confined to the interior of the winding, the magnetic flux density being substantially zero outside it.
2) The shape of the toroidal coil is such that it can occupy approximately the same space a high power transistor would occupy in comparison to a solenoid that could be very long.

However, in low power applications, where the required magnetic energy is small, a conventional coil can be used.

The lower section of the circuit output of Fig. 3 consists of a current driving power transistor and the necessary components to provide initial current spiking. The spiking feature of the driver is needed to achieve good p-i-n diode current rise time[4]. The reverse-bias is the quiescent stage for the driver. Under this state the p-i-n diodes are in their off condition and only a small leakage current is provided to them through resistor R_T. Capacitor C_S,called switching capacitor, prior to each forward-bias transition is charged by the voltage source V_S to a voltage level which is more negative than the voltage V_F. When a forward-bias signal (positive pulse) is applied to the input of the driver, transistor Q turns on and a relatively high current flows from the p-i-n diode load to the negatively charged capacitor C_S. Thus, the needed initial current spike is formed and the p-i-n diodes accumulate their rated storage charge rapidly. As time elapses, this current diminishes toward its steady state value flowing through diode D_2 to the voltage source V_F. During this transition a current flows, also, through the toroidal coil L_T and magnetic energy is stored in it. However, the current rise through the toroidal coil will depend on the duration of the forward-bias signal, i.e on the requirement of switching between the two states. The forward-bias duration is typically long enough to allow steady state current levels to be reached. At higher repetition rates, the parameters of the circuit must be such that they will insure a minimum required current to produce a minimum reverse voltage during the discharging of the toroidal coil to p-i-n diodes.

When a reverse-bias signal (appr. zero volt) is applied to the input of the driver, transistor Q turns off. Then, the energy that was stored in the toroidal coil flows to p-i-n diodes to reverse their charge and charge up the parasitic capacitance C_P. At the end of this transition the p-i-n diodes reach again their reverse-bias steady state condition. During design, care must be taken so that

$$E_T \geq E_D + E_p \qquad (1)$$

where E_T is the energy to be stored in the toroidal coil, E_D is the energy required to reverse the stored charge of the p-i-n diodes and E_p is the energy required to charge up the parasitic capacitance to the reverse bias voltage level. Since E_T is related to the inductance of the toroidal coil and the forward-bias current, and the amount of the other two energies is known, the value of the required inductance for the toroidal coil can be determined from (1).

Regions of Switching and First Order Models.

During normal switching operation a p-i-n diode can assume four different states:

Reverse-bias steady state
Forward-bias steady state
Switching from reverse-bias to forward-bias
Switching from forward-bias to reverse-bias

Here we are concerned primarily about the two switching or transition states, while the other two states constitute the initial and final conditions of the circuit. In order to be able to follow the development of voltage and current waveforms, we divide each transition state into piecewise regions as follows:

1) For the reverse-bias to forward-bias transition:
   a) Transistor turn on.
   b) P-i-n diode forward-bias current through switching capacitor.
   c) P-i-n diode forward-bias current through dc power supply.
2) For the forward-bias to reverse-bias transition:
   a) Transistor turn off.
   b) Slow current change.
   c) Voltage rise and current Fall.

It is to be noted that during the transition states, only dc-bias levels are considered and no high RF power is applied to p-i-n diode phase shifters, or it is interrupted just prior to their switching initiation. High RF power is not allowed during the p-i-n diode switching, because it increases the insertion loss and may damage these devices. Since we are dealing with large signals and assume no RF present during switching, first order dc models (see Fig. 4) suffice to examine the p-i-n diode circuit behavior.

Figure 4a shows the first order p-i-n dc-model for the reverse-bias steady state. The p-i-n diode junction capacitance (C_j), that actually is in parallel with the parasitic capacitance (C_p), has been omitted because $C_j \ll C_p$. Sometimes the reverse-bias resistance (R_p) is also omitted and this model reduces to a single capacitor C_p charged to the full reverse-bias voltage level.

In the forward-bias steady state, the p-i-n diode capacitance-a fictitious capacitance C_F-is very large (see Fig. 4b) and the parasitic capasitance C_p can be omitted because $C_p \ll C_F$. In this state the p-i-n diodes have accumulated their rated storage charge (Q_d) and the voltage across them has an average value $V_{DF} \approx -0.7\,V$ for the mounting polarity shown in Fig. 3.

For the transition from reverse-bias to forward-bias the first-order charge control model, shown in Fig. 4c, can be used. Mathematically, the forward dc current condition can be described by the continuity or charge-control equation for the charge q(t) in the I-layer

$$i(t)=dq(t)/dt+q(t)/\tau, \qquad (2)$$

where τ is the p-i-n diode minority carrier life time.

During the transition from forward-bias to reverse-bias, and particularly after the p-i-n diode voltage has started reversing, the capacitance C_F changes to a space charge impedance (resistance). The average space charge resistance, designated by R_{sc}, is given by

$$R_{sc} = w/2\bar{v}_c\, C_j, \qquad (3)$$

where w is the width of p-i-n diode I-layer, $\bar{v}_c$ is the average velocity of carriers in the space charge layers and C_j is the p-i-n diode junction capacitance. Thus, when the voltage starts reversing, the p-i-n diode load can be represented by an equivalent resistive element R_{sc} in parallel with the parasitic capacitance as shown in Fig. 4d.

Brief Analysis of Each Region

For each region, an equivalent circuit can be drawn and analyzed using an appropriate model from Fig. 4. Here, however, we shall not go into a detailed analysis. Instead, a few guidelines will be given as needed for following the switching process. It is to be noted that parallel work is under way to develop detailed equations for the current and voltage waveforms in each region and the results will be available for publication in the near future.

In the following brief analysis, v_d will represent the voltage across the p-i-n diodes and the parasitic capacitance, while i_d will represent the current through the two p-i-n diode load including the parasitic capacitance.

Reverse-Bias to Forward-Bias Transition.

Transistor Turn On.

Upon initiation of a forward-bias signal to the driver (see Fig. 3) at $t=t_0$, there will not be any response until time t_1, which is the forward-bias delay time of the driving circuitry. Initially, the current through transistor Q will be

$$i_d(t)=\beta_F I_B \left\{1-\exp\left[-(t-t_1)/\tau_1\right]\right\}, \quad t_1 \leq t \leq t_2 \qquad (4)$$

where $\tau_1 \approx \beta_F/2\pi f_T$. This current represents primarily the p-i-n diode junction and parasitic capacitance discharging current. The current rise in the toroidal coil is negligible, as well as the current provided by V_R because R_r is very large. The voltage in the p-i-n diode load is given by

$$v_d(t)=(1/C_p)\int_{t_1}^{t} i_d(t)dt+V_R, \quad t_1 \leq t \leq t_2 \qquad (5)$$

At the end of this region, transistor Q has turned on and the voltage across the p-i-n diodes is approximately equal to -0.7 V.

P-i-n Diode Forward-Bias Current Through Switching Capacitor.

Once the voltage across the p-i-n diodes has become -0.7 V, it remains approximately at that level throughout this region and the next region. The p-i-n diode and toroidal coil currents flow to the negatively charged capacitor C_s. During this transition the p-i-n diodes accumulate their storage charge.

P-i-n Diode Forward-Bias Current Through the Power Supply.

The previous region ends when the voltage across the switching capacitor has become

$$V_s' = - V_F - V_{D2}. \qquad (6)$$

The p-i-n diode current reaches its steady state in the beginning of this region, whereas the toroidal coil current reaches its steady state at a later time due to a long time constant involved.

Forward-Bias to Reverse-Bias Transition.

Transistor Turn Off.

When a reverse-bias signal is applied to the driver of Fig. 3 at $t=t_o$, there will not be any response until time t_1 which represents the circuit propagation delay and the transistor storage time. As transistor Q turns off, a reverse current starts flowing to p-i-n diodes given by

$$i_d(t)=-I_T+(I_T+I_F)\exp\left[-(t-t_1)/\tau_1\right], \quad t_1\leq t\leq t_2 \qquad (7)$$

where I_F and I_T are the p-i-n diode load and toroidal coil steady state currents, respectively. The voltage of the p-i-n diodes remains small and negative throughout this region.

Slow Current Change.

In this region the current is changing very slowly due to the removal of the bulk of the p-i-n diode storage charge. The voltage, also, changes slowly toward zero and at the end of the region it starts reversing.

Voltage Rise and Current Fall.

Since the bulk of the p-i-n diode storage charge has been removed, a voltage rise and a current fall occur with a time constant which is a combination of the driving circuit parameters and the model of Fig. 4d. At the end of this transition, the current becomes almost zero. If v_d exceeds the V_R level, it is clamped to that level by diode D_4. On the contrary, if it is smaller, it is "pulled up" to that level through R_r.

Experimental Work

The circuit of Fig. 3 was breadboarded using discrete components. Typical values of all key components of the output circuit are listed in Table I. All other circuit elements can be adjusted or changed to meet the requirements of the output circuit. Figure 5 shows the forward-bias switching waveforms for the inductive driver, where there is a good current spike. Figure 6 represents the same transition but without current spike and a stretching in the voltage drop. These waveforms are obtained by shorting out the diode D2 in Fig. 3.

Table I

Typical Values of Key Components of Fig. 3

R_D : 3.75Ω	V_R : 200 VDC
R_T : 2.2 Ω	V_F : (-)2.85 VDC
R_r : 50 kΩ	D_1 -D_4 : 1N4936
L_T : 0.4 mH	Q : BUX80
C_p : 1000pF	P-i-n : MA-47893

The reverse-bias switching waveforms for the inductive driver are shown in Fig. 7. Figure 8 shows the reverse-bias switching waveforms for a conventional driver with two output transistors. Since the current in the two-transistor circuit is provided by an external source, it is higher in amplitude and shorter in duration than the current in Fig. 7. Also, the rounding top of the current and the ending of voltage in these waveforms, compared to the current flat top and the voltage overshoot of Fig. 7, indicate different driving circuit and p-i-n diode load interactions for these circuits

Conclusion

The use of a toroidal coil to replace one of the circuit output high power transistors, in medium or high power p-i-n diode driving applications, has been investigated and experimental results have been obtained. The technique is particularly useful in cases where the benefits of economy and higher reliability are more desirable than the relatively higher switching speed of the conventional totem-pole circuits.

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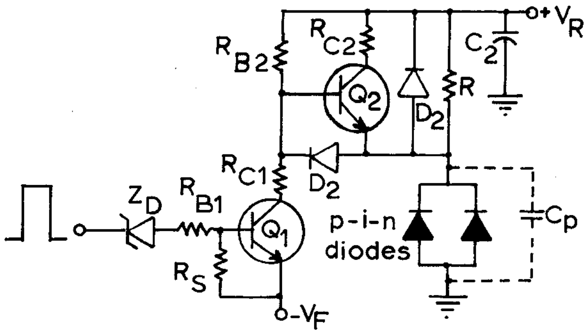

Fig. 1-Typical p-i-n diode driver with totem-pole transistor configuration.

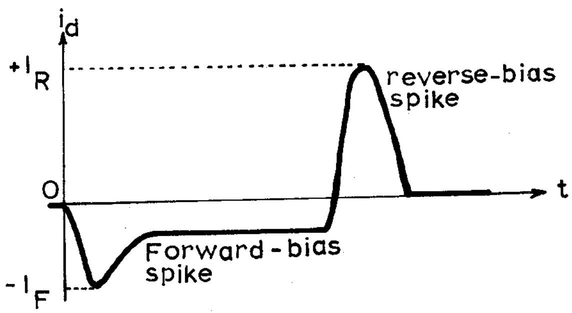

Fig. 2-Desirable high current spikes in p-i-n diode switching.

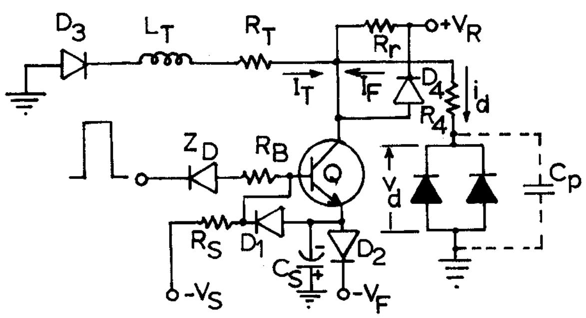

Fig. 3-Inductive p-i-n diode driver with single transistor output.

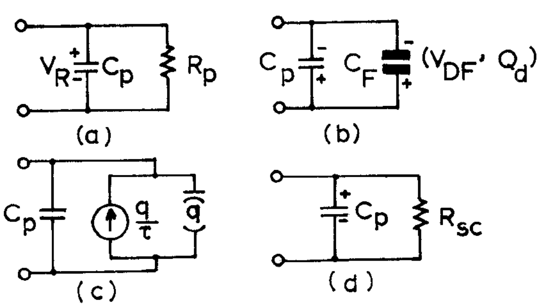

Fig. 4-First order p-i-n diode load dc-models for: Forward-bias steady state (a), reverse-bias steady state(b), forward-bias transition (c) and reverse-**bias transition** (d).

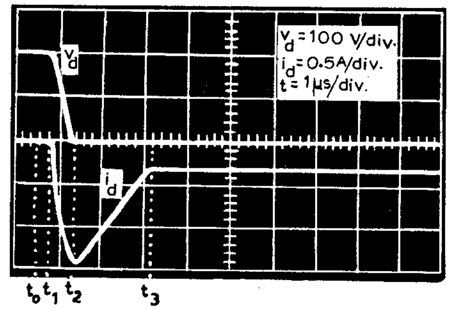

Fig. 5-Waveforms for forward-bias switching of inductive driver with current spike.

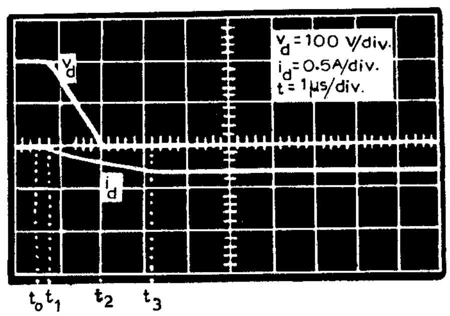

Fig. 6-Waveforms for forward-bias switching of inductive driver with D_2 shorted

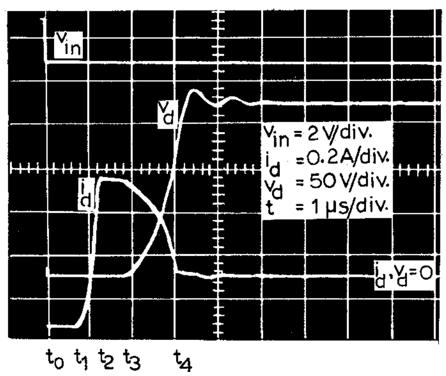

Fig. 7-Waveforms for reverse-bias switching of inductive driver.

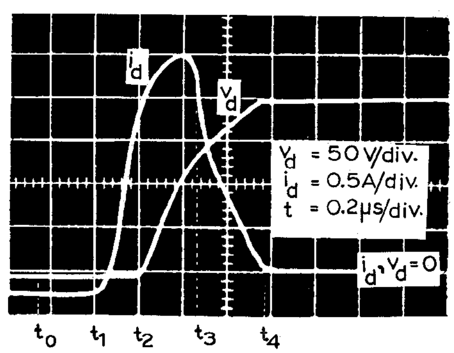

Fig. 8-Waveforms for reverse-bias switching of driver with totem-pole outputs(Ref.3).